WEST

# Freeform Search

**Database:**
US Patents Full-Text Database
US Pre-Grant Publication Full-Text Database
JPO Abstracts Database
EPO Abstracts Database
Derwent World Patents Index
IBM Technical Disclosure Bulletins

**Term:** L30 and (switch$4)

**Display:** 100 **Documents in Display Format:** - **Starting with Number** 1

**Generate:** ○ Hit List ◉ Hit Count ○ Side by Side ○ Image

Search | Clear | Help | Logout | Interrupt

Main Menu | Show S Numbers | Edit S Numbers | Preferences | Cases

## Search History

**DATE: Thursday, August 14, 2003** Printable Copy Create Case

| Set Name side by side | Query | Hit Count | Set Name result set |
|---|---|---|---|
| | *DB=USPT,PGPB,JPAB,EPAB,DWPI,TDBD; PLUR=YES; OP=ADJ* | | |
| L32 | L30 and (switch$4) | 13 | L32 |
| L31 | L30 and (load$4) | 11 | L31 |
| L30 | L29 and (SCR or (silicon with controlled with rectifier)) | 13 | L30 |
| L29 | L28 and (phase or portion or path or part or rout$4) | 89 | L29 |
| L28 | L27 and (bias or value or threshold$4 or amount or thresh-hold$4 or cutoff or cut-off or "cut off" or limit$4) | 90 | L28 |
| L27 | L26 and (conduct$6) | 90 | L27 |
| L26 | L25 and (pulse) | 106 | L26 |
| L25 | L24 and (gradient with (amplifier or assembly or coil or sequence or control$5)) | 121 | L25 |
| L24 | L23 and (parallel or series) | 140 | L24 |

| | | | |
|---|---|---|---|
| L23 | L22 and ((magnitude or amplitude or intensity) with (control$4 or regulat$5 or steer$4 or direct$4 or operat$7) with (switch$5)) | 151 | L23 |
| L22 | L21 and ((control$4 or regulat$5 or steer$4 or direct$4 or operat$7) with (switch$5)) | 1250 | L22 |
| L21 | L20 and (current) | 7431 | L21 |
| L20 | L2 and (magnitude or amplitude or intensity) | 12481 | L20 |
| L19 | L17 and (steer$4 or direct$6) | 2 | L19 |
| L18 | L17 and L8 | 1 | L18 |
| L17 | L16 and (current) | 2 | L17 |
| L16 | L15 and (phase or portion or path) | 2 | L16 |
| L15 | L14 and (first or second or third or fourth or one or two or three or four) | 2 | L15 |
| L14 | L13 and (magnitude or amplitude or intensity) | 2 | L14 |
| L13 | L12 and (parallel or series) | 3 | L13 |
| L12 | L11 and (bias or value or threshold$4) | 3 | L12 |
| L11 | L10 and (sequence) | 3 | L11 |
| L10 | L9 and (transistor) | 5 | L10 |
| L9 | L7 and (diode or antiparallel or anti-parallel or back-to-back or "back to back") | 14 | L9 |
| L8 | L7 and (SCR or (silicon with controlled with rectifier)) | 1 | L8 |
| L7 | L6 and (pulse) | 110 | L7 |
| L6 | L5 and (conduct$6) | 111 | L6 |
| L5 | L4 and (switch$6) | 295 | L5 |
| L4 | L3 and (gradient with amplifier with assembly) | 413 | L4 |
| L3 | L2 and (gradient with (amplifier or assembly or coil)) | 5523 | L3 |
| L2 | L1 and (gradient) | 30518 | L2 |
| L1 | ((magnetic adj resonance) or MRI or NMR) | 153966 | L1 |

END OF SEARCH HISTORY

# WEST

Generate Collection | Print

**Search Results -** Record(s) 1 through 1 of 1 returned.

☐ 1. Document ID: US 4820986 A

L8: Entry 1 of 1 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Mansfield; Peter | Beeston | | | GB |
| Coxon; Ronald J. | Wollaton | | | GB |

US-CL-CURRENT: 324/322; 363/98

Full | Title | CIT.1 | REV.1 | CLS.1 | REF.1 | SEQ.1 | ATT.1 | KAW.1

Generate Collection | Print

| Term | Documents |
|---|---|
| SCR | 22334 |
| SCRS | 3498 |
| SILICON | 742040 |
| SILICONS | 1348 |
| CONTROLLED | 2139881 |
| CONTROLLEDS | 3 |
| RECTIFIER | 121881 |
| RECTIFIERS | 24961 |
| (7 AND (SCR OR (RECTIFIER WITH SILICON WITH CONTROLLED))).USPT,PGPB,JPAB,EPAB,DWPI,TDBD. | 1 |
| (L7 AND (SCR OR (SILICON WITH CONTROLLED WITH RECTIFIER))).USPT,PGPB,JPAB,EPAB,DWPI,TDBD. | 1 |

**Display Format:** - Change Format

Previous Page Next Page

WEST

Generate Collection | Print

**Search Results -** Record(s) 1 through 2 of 2 returned.

---

☐ 1. Document ID: US 5270657 A

L19: Entry 1 of 2 File: USPT Dec 14, 1993

US-PAT-NO: 5270657
DOCUMENT-IDENTIFIER: US 5270657 A

TITLE: Split gradient amplifier for an MRI system

DATE-ISSUED: December 14, 1993

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Wirth; William F. | Sullivan | WI | | |
| McFarland; Thomas G. | Hartland | WI | | |
| Vavrek; Robert M. | Waukesha | WI | | |
| Roemer; Peter B. | Schenectady | NY | | |
| Mueller; Otward M. | Ballston Lake | NY | | |
| Park; John N. | Rexford | NY | | |

US-CL-CURRENT: 324/322; 324/318

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC | Draw Desc | Image

---

☐ 2. Document ID: US 4820986 A

L19: Entry 2 of 2 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Mansfield; Peter | Beeston | | | GB |
| Coxon; Ronald J. | Wollaton | | | GB |

US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC | Draw Desc | Image

---

Generate Collection | Print

| Term | Documents |
|---|---|
| STEER$4 | 0 |
| STEER | 68415 |
| STEERA | 5 |
| STEERABE | 1 |
| STEERABIE | 2 |
| STEERABLE | 20232 |
| STEERABLY | 697 |
| STEERAB1E | 1 |
| STEERAGE | 944 |
| STEERAGEA | 1 |
| STEERAGES | 6 |
| (L17 AND (STEER$4 OR DIRECT$6)).USPT,PGPB,JPAB,EPAB,DWPI,TDBD. | 2 |

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**Display Format:** - | Change Format

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# WEST

Generate Collection | Print

**Search Results -** Record(s) 1 through 13 of 13 returned.

---

☐ 1. Document ID: US 20020183638 A1

L30: Entry 1 of 13 File: PGPB Dec 5, 2002

PGPUB-DOCUMENT-NUMBER: 20020183638
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020183638 A1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

PUBLICATION-DATE: December 5, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Swanson, David K. | Mountain View | CA | US | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw. Desc | Image

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☐ 2. Document ID: US 20020147470 A1

L30: Entry 2 of 13 File: PGPB Oct 10, 2002

PGPUB-DOCUMENT-NUMBER: 20020147470
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020147470 A1

TITLE: Electromagnetic interference immune tissue invasive system

PUBLICATION-DATE: October 10, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Weiner, Michael L. | Webster | NY | US | |
| Helfer, Jeffrey L. | Webster | NY | US | |
| Connelly, Patrick R. | Rochester | NY | US | |
| MacDonald, Stuart G. | Pultneyville | NY | US | |
| Miller, Victor | Clarence | NY | US | |

US-CL-CURRENT: 607/9

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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## 3. Document ID: US 20020143258 A1

L30: Entry 3 of 13 File: PGPB Oct 3, 2002

PGPUB-DOCUMENT-NUMBER: 20020143258
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020143258 A1

TITLE: Electromagnetic interference immune tissue invasive system

PUBLICATION-DATE: October 3, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Weiner, Michael L. | Webster | NY | US | |
| Helfer, Jeffrey L. | Webster | NY | US | |
| Connelly, Patrick R. | Rochester | NY | US | |
| MacDonald, Stuart G. | Pultneyville | NY | US | |
| Miller, Victor | Clarence | NY | US | |

US-CL-CURRENT: 600/476

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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## 4. Document ID: US 20010012918 A1

L30: Entry 4 of 13 File: PGPB Aug 9, 2001

PGPUB-DOCUMENT-NUMBER: 20010012918
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20010012918 A1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

PUBLICATION-DATE: August 9, 2001

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Swanson, David K. | Mountain View | CA | US | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

---

## 5. Document ID: US 6428537 B1

L30: Entry 5 of 13 File: USPT Aug 6, 2002

US-PAT-NO: 6428537
DOCUMENT-IDENTIFIER: US 6428537 B1

TITLE: Electrophysiological treatment methods and apparatus employing high voltage pulse to render tissue temporarily unresponsive

DATE-ISSUED: August 6, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |
| Whayne; James G. | Saratoga | CA | | |

US-CL-CURRENT: 606/41; 607/122

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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6. Document ID: US 6421556 B2

L30: Entry 6 of 13 File: USPT Jul 16, 2002

US-PAT-NO: 6421556
DOCUMENT-IDENTIFIER: US 6421556 B2

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: July 16, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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7. Document ID: US 6369465 B1

L30: Entry 7 of 13 File: USPT Apr 9, 2002

US-PAT-NO: 6369465
DOCUMENT-IDENTIFIER: US 6369465 B1
**** See image for Certificate of Correction ****

TITLE: Power supply for use in electrophysiological apparatus employing high-voltage pulses to render tissue temporarily unresponsive

DATE-ISSUED: April 9, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 307/112; 307/115

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

## ☐ 8. Document ID: US 6212426 B1

L30: Entry 8 of 13 File: USPT Apr 3, 2001

US-PAT-NO: 6212426
DOCUMENT-IDENTIFIER: US 6212426 B1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: April 3, 2001

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 600/510; 606/34

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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## ☐ 9. Document ID: US 6107699 A

L30: Entry 9 of 13 File: USPT Aug 22, 2000

US-PAT-NO: 6107699
DOCUMENT-IDENTIFIER: US 6107699 A

TITLE: Power supply for use in electrophysiological apparatus employing high-voltage pulses to render tissue temporarily unresponsive

DATE-ISSUED: August 22, 2000

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 307/112; 307/115

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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## ☐ 10. Document ID: US 6023638 A

L30: Entry 10 of 13 File: USPT Feb 8, 2000

US-PAT-NO: 6023638
DOCUMENT-IDENTIFIER: US 6023638 A

TITLE: System and method for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: February 8, 2000

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 600/510; 606/41

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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## 11. Document ID: US 5684402 A

L30: Entry 11 of 13 File: USPT Nov 4, 1997

US-PAT-NO: 5684402
DOCUMENT-IDENTIFIER: US 5684402 A
**** See image for Certificate of Correction ****

TITLE: Gradient coil power supply and imaging method

DATE-ISSUED: November 4, 1997

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Rohan; Michael L. | Cambridge | MA | | |
| Evans; Robert R. | Framingham | MA | | |

US-CL-CURRENT: 324/322; 324/318

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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## 12. Document ID: US 5521507 A

L30: Entry 12 of 13 File: USPT May 28, 1996

US-PAT-NO: 5521507
DOCUMENT-IDENTIFIER: US 5521507 A

TITLE: Gradient coil power supply and imaging method

DATE-ISSUED: May 28, 1996

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Rohan; Michael L. | Cambridge | MA | | |
| Evans; Robert R. | Framingham | MA | | |

US-CL-CURRENT: 324/322; 324/318

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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## 13. Document ID: US 4820986 A

L30: Entry 13 of 13 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Mansfield; Peter | Beeston | | | GB |
| Coxon; Ronald J. | Wollaton | | | GB |

US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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| Term | Documents |
|---|---|
| SCR | 22334 |
| SCRS | 3498 |
| SILICON | 742040 |
| SILICONS | 1348 |
| CONTROLLED | 2139881 |
| CONTROLLEDS | 3 |
| RECTIFIER | 121881 |
| RECTIFIERS | 24961 |
| (29 AND (SCR OR (RECTIFIER WITH SILICON WITH CONTROLLED))).USPT,PGPB,JPAB,EPAB,DWPI,TDBD. | 13 |
| (L29 AND (SCR OR (SILICON WITH CONTROLLED WITH RECTIFIER))).USPT,PGPB,JPAB,EPAB,DWPI,TDBD. | 13 |

**Display Format:** - Change Format

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**Search Results** - Record(s) 1 through 11 of 11 returned.

1. Document ID: US 20020183638 A1

L31: Entry 1 of 11 File: PGPB Dec 5, 2002

PGPUB-DOCUMENT-NUMBER: 20020183638
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020183638 A1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

PUBLICATION-DATE: December 5, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Swanson, David K. | Mountain View | CA | US | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

2. Document ID: US 20020147470 A1

L31: Entry 2 of 11 File: PGPB Oct 10, 2002

PGPUB-DOCUMENT-NUMBER: 20020147470
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020147470 A1

TITLE: Electromagnetic interference immune tissue invasive system

PUBLICATION-DATE: October 10, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Weiner, Michael L. | Webster | NY | US | |
| Helfer, Jeffrey L. | Webster | NY | US | |
| Connelly, Patrick R. | Rochester | NY | US | |
| MacDonald, Stuart G. | Pultneyville | NY | US | |
| Miller, Victor | Clarence | NY | US | |

US-CL-CURRENT: 607/9

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 3. Document ID: US 20020143258 A1

L31: Entry 3 of 11 File: PGPB Oct 3, 2002

PGPUB-DOCUMENT-NUMBER: 20020143258
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020143258 A1

TITLE: Electromagnetic interference immune tissue invasive system

PUBLICATION-DATE: October 3, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Weiner, Michael L. | Webster | NY | US | |
| Helfer, Jeffrey L. | Webster | NY | US | |
| Connelly, Patrick R. | Rochester | NY | US | |
| MacDonald, Stuart G. | Pultneyville | NY | US | |
| Miller, Victor | Clarence | NY | US | |

US-CL-CURRENT: 600/476

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 4. Document ID: US 20010012918 A1

L31: Entry 4 of 11 File: PGPB Aug 9, 2001

PGPUB-DOCUMENT-NUMBER: 20010012918
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20010012918 A1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

PUBLICATION-DATE: August 9, 2001

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Swanson, David K. | Mountain View | CA | US | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 5. Document ID: US 6428537 B1

L31: Entry 5 of 11 File: USPT Aug 6, 2002

US-PAT-NO: 6428537
DOCUMENT-IDENTIFIER: US 6428537 B1

TITLE: Electrophysiological treatment methods and apparatus employing high voltage pulse to render tissue temporarily unresponsive

DATE-ISSUED: August 6, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |
| Whayne; James G. | Saratoga | CA | | |

US-CL-CURRENT: 606/41; 607/122

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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6. Document ID: US 6421556 B2

L31: Entry 6 of 11 File: USPT Jul 16, 2002

US-PAT-NO: 6421556
DOCUMENT-IDENTIFIER: US 6421556 B2

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: July 16, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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7. Document ID: US 6369465 B1

L31: Entry 7 of 11 File: USPT Apr 9, 2002

US-PAT-NO: 6369465
DOCUMENT-IDENTIFIER: US 6369465 B1
**** See image for Certificate of Correction ****

TITLE: Power supply for use in electrophysiological apparatus employing high-voltage pulses to render tissue temporarily unresponsive

DATE-ISSUED: April 9, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 307/112; 307/115

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

☐ 8. Document ID: US 6212426 B1

L31: Entry 8 of 11 File: USPT Apr 3, 2001

US-PAT-NO: 6212426
DOCUMENT-IDENTIFIER: US 6212426 B1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: April 3, 2001

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 600/510; 606/34

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments KWIC
Draw Desc | Image

☐ 9. Document ID: US 6107699 A

L31: Entry 9 of 11 File: USPT Aug 22, 2000

US-PAT-NO: 6107699
DOCUMENT-IDENTIFIER: US 6107699 A

TITLE: Power supply for use in electrophysiological apparatus employing high-voltage pulses to render tissue temporarily unresponsive

DATE-ISSUED: August 22, 2000

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 307/112; 307/115

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments KWIC
Draw Desc | Image

☐ 10. Document ID: US 6023638 A

L31: Entry 10 of 11 File: USPT Feb 8, 2000

US-PAT-NO: 6023638
DOCUMENT-IDENTIFIER: US 6023638 A

TITLE: System and method for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: February 8, 2000

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 600/510; 606/41

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

☐ 11. Document ID: US 4820986 A

L31: Entry 11 of 11 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Mansfield; Peter | Beeston | | | GB |
| Coxon; Ronald J. | Wollaton | | | GB |

US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

Generate Collection | Print

| Term | Documents |
|---|---|
| LOAD$4 | 0 |
| LOAD | 1302389 |
| LOADA | 34 |
| LOADABLC | 1 |
| LOADABLE | 6969 |
| LOADABLY | 287 |
| LOADAC | 3 |
| LOADACC | 2 |
| LOADACR | 1 |
| LOADACT | 4 |
| LOADAD | 12 |
| (L30 AND (LOAD$4)).USPT,PGPB,JPAB,EPAB,DWPI,TDBD. | 11 |

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**Display Format:** [ - ] [ Change Format ]

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End of Result Set

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L31: Entry 11 of 11 File: USPT Apr 11, 1989

DOCUMENT-IDENTIFIER: US 4820986 A
TITLE: Inductive circuit arrangements

Abstract Text (1):
A switched coil arrangement is connected in a bridge configuration of four switches S.sub.1, S.sub.2, S.sub.3 and S.sub.4 which are each shunted by diodes D.sub.1, D.sub.2, D.sub.3 and D.sub.4 so that current can flow in either direction through a coil L depending on the setting of the switches. A capacitor C is connected across the bridge through a switch S.sub.5 to receive the inductive energy stored in coil L on breaking the current flow path through the coil. The electrostatic energy stored in capacitor C can then be used to supply current through the coil in the reverse direction either immediately or after a time delay. Coil L may be a superconductive coil. Losses in the circuit can be made up by a trickle charge of capacitor C from a separate supply V.sub.2.

Brief Summary Text (1):
This invention relates to inductive circuit arrangements and is concerned with arrangements which enable the current flow through an inductive coil to be rapidly switched on and off or reversed.

Brief Summary Text (2):
In many applications of nuclear magnetic resonance (NMR) it is often required to switch on or off or to reverse magnetic fields and especially magnetic gradient fields and to effect such switching or reversal as rapidly as possible. Switching of magnetic gradient fields is important in NMR imaging applications especially where high speed is required. An example of such an application is in the echo planar imaging (EPI) technique as described in British Pat. No. 1,596,160. In EPI there is a requirement to switch trapezoidal gradient fields with a switching time of around 25 .mu.s for best effect. These gradient fields are created by passing electrical currents through inductive coil arrangements which may have non-zero resistance. For low resolution imaging low currents and small coil assemblies can be utilised and it is possible to use linear amplifiers to achieve the required switching rates and gradient amplitudes. However if high resolution is required larger gradient fields must be employed and to achieve the required high switching rates extremely high power amplifiers are necessary. It is believed that this is one of the major obstacles to the commercial development of ultra high-speed NMR imaging techniques like EPI.

Brief Summary Text (3):
The power requirements for the rapid switching of current through an inductance will be appreciated from a consideration of the theoretical background. Let a step voltage V be applied to an inductance L through a resistor r then the size of current i is given by the well known expression

Brief Summary Text (8):
For very low winding resistance, this power can be made arbitrarily low. However, for a given value of inductance L and rise time, equation (5) determines the peak power requirements of the driver amplifier. For linear amplifiers this situation presents something of a dilemma. Peak powers and voltages exceeding the capability of the amplifier may be required for short durations only, in order to establish the steady state current I. Then according to equation (6), the power requirement may drop to an arbitrarily low figure, though I may be high.

Brief Summary Text (9):
Linear amplifiers with both high voltage and high current capability are not readily

available but in any event are an inefficient and uneconomic approach for gradient switching.

Brief Summary Text (10):
For superconductive coils, r=0 so that .tau..fwdarw..infin., equation (3). In this case, it would take an infinite time (in practice a long time) to establish any current through L. But having established a current, no power would be required to maintain it.

Brief Summary Text (12):
According to the invention an inductive circuit arrangement comprises four switches connected in a bridge configuration, current supply terminals to opposite ends of the bridge, inductive coil means connected across the bridge so that current can flow in either direction through the coil means depending on the setting of the switches, a series connection of capacitor means and a switch connected across the supply terminals, and means for operating the said switches so as to connect the capacitor means across the coil means at least for a sufficient period of time until the current flow through the coil reduces to zero by charging of the capacitor means.

Brief Summary Text (13):
In carrying out the invention the said means for operating the switches may function subsequently to allow the capacitor means to discharge to generate current flow through the coil means in the opposite direction to the initial flow.

Brief Summary Text (14):
Preferably the said switches are shunted by unidirectional current flow devices.

Brief Summary Text (15):
It will be seen that in the operation of the above circuit arrangement the magnetic energy stored in the inductive coil is not destroyed but is transformed to electrostatic energy for storage in the capacitor means. Thus the power required to switch or reverse the current through the coil is theoretically zero since the total energy of the system comprising coil and capacitor is constant. In practice there will be minor energy losses but these can be compensated for by provided trickle charge means connected to the capacitor means to enable the capacitor means to be charged to a predetermined voltage value after discharge. It is desirable to ensure that the said predetermined voltage is greater than the voltage across the supply terminals.

Brief Summary Text (16):
It may be desirable to connect a unidirectional current flow device in series with the current supply terminals to prevent flow of current through the current supply terminals in the reverse direction.

Brief Summary Text (18):
To provide start-up energy for the circuit initiating charge means comprising an additional power supply can be connected through a switch to initially charge the capacitor means to a peak voltage to provide the requisite electrical energy to establish the required current flow in the said coil means.

Brief Summary Text (19):
It may also be desirable to provide a switched parallel path across the bridge to maintain a substantially constant value of current through the current supply terminals irrespective of the settings of the switches in the bridge configuration.

Brief Summary Text (20):
In one embodiment of the invention the bridge configuration is so modified that the two arms of the bridge are connected to different current supply terminals and separate series connections each of a capacitor means and a switch are connected to each supply terminal so as to enable different values of current flow to be established through the coil in respective opposite directions.

Brief Summary Text (21):
In certain embodiments of the invention the capacitor means is used as a temporary energy store only and a second inductive coil means is provided as a more long-term store. Such an arrangement is useful where immediate current reversal in an operating coil is not required. In one such embodiment a further bridge configuration with associated further current supply terminals is provided with a further inductive coil means connected across the said further bridge configuration and the capacitor means is also connected in series with a further switch across the further current supply

terminals. With such an arrangement the energy in the operating coil is first transferred to the capacitor means in the manner described above and is then transferred to the further inductive coil means where it can be stored indefinitely, with any losses if need be being made up from the voltage source connected across the further current supply terminals.

Drawing Description Text (5):
FIG. 4 is a circuit embodying the invention for enabling opposite current flows in a coil to have different amplitudes,

Drawing Description Text (6):
FIG. 5 illustrates various current waveforms possible by using the invention,

Detailed Description Text (1):
Referring now to FIG. 1 there is illustrated therein a bridge configuration of four switches S.sub.1, S.sub.2, S.sub.3 and S.sub.4. Each switch is shunted by a respective diode D.sub.1, D.sub.2, D.sub.3 or D.sub.4. All the diodes are conductive in the same direction. An inductive coil L is connected across the bridge between points A and B. The bridge has current supply terminals T.sub.1 and T.sub.2, terminal T.sub.2 being earthed and terminal T.sub.1 being supplied from a voltage or current supply V.sub.1 through a diode D.sub.6. A series connection of a capacitor C and switch S.sub.5 is connected across the bridge between terminals T.sub.1 and T.sub.2 and switch S.sub.5 is shunted by a diode D.sub.5. Capacitor C can be charged from a voltage supply V.sub.2 through a diode D.sub.7 and resistor R.sub.1. The various switches S.sub.1 to S.sub.5 are controlled by signals applied along lines G.sub.1 to G.sub.5 respectively.

Detailed Description Text (2):
To understand the operation of the circuit shown in FIG. 1 let it be assumed initially that switches S.sub.1 and S.sub.4 are closed and that switches S.sub.2 and S.sub.3 are open. With this arrangement of the switches current will flow through coil L from terminal A to terminal B. If now at a time t=0 switches S.sub.1 and S.sub.4 are switched off simultaneously the magnetic field in coil L will collapse and will generate an emf across the coil and by Lenz's law point A will be negative with respect to point B. Point A is clamped to earth terminal T.sub.2 through diode D.sub.3 and since point B is therefore positive there will be a continuous path for the current flowing in coil L through diodes D.sub.2 and D.sub.3, diode D.sub.5 and capacitor C. The energy in coil L will therefore be dumped into capacitor C where it will be stored as electrostatic energy. While this charging of capacitor C takes place switches S.sub.2 and S.sub.3 can be closed but the timing of their closure is not critical since current is flowing during this time through diodes D.sub.2 and D.sub.3. Switch S.sub.5 is also closed during this time without affecting the operation of the circuit. The current through coil L reaches zero at a time t=t.sub.s at which instant capacitor C becomes fully charged to a peak value of voltage V.sub.c. The time t.sub.s is defined by

Detailed Description Text (3):
The current flow will reverse through the now closed switches S.sub.2, S.sub.3 and S.sub.5 and capacitor C will entirely discharge to generate a current flow of magnitude-I from B to A in the reverse direction through coil L after a time 2t.sub.s.

Detailed Description Text (6):
the energy transfer time or switching time, t.sub.s, can be chosen by an appropriate value of C. The capacitor voltage V.sub.c during a switch, is shown in FIG. 2(a). At t=0, V.sub.c =V.sub.2. After energy transfer at t=t.sub.s, V.sub.c =V.sub.c. Capacitor C discharges in the next 1/4-cycle through closed switch S.sub.5. The discharge path is through switches S.sub.2 and S.sub.3 thereby establishing a reversed current, -I, through coil L. At the end of the discharge period, when t=2t.sub.s, V.sub.c .perspectiveto.0 and at this point in time switch S.sub.5 is opened isolating C from the circuit. Thereafter the capacitor is trickle charged through resistor R.sub.1 until V.sub.c =V.sub.2.

Detailed Description Text (7):
The voltage V.sub.A across the terminals T.sub.1 and T.sub.2 and the current i.sub.L through coil L are shown in FIG. 2(b) and FIG. 2(c) respectively. Prior to reversal, V.sub.A .perspectiveto.V.sub.1 and i.sub.L =I. At time t=t.sub.s, i.sub.L =0 and V.sub.A =V.sub.c. The diode D.sub.6 protects the low voltage power supply during the switching operation and allows a smooth transition back to V.sub.1 following current reversal. Since D.sub.1 conducts when S.sub.1 is switched off, a smooth transition from I to -I obtains, with no discontinuous glitches at the zero-crossing.

Detailed Description Text (10):
The operation of the circuit of FIG. 1 assumed an initial steady state current flowing in the coil. However, from FIG. 2 it can be seen that at time t=t.sub.s, i.sub.L =0. That is to say, the circuit is switched off. The conditions to switch on from i.sub.L =0 are therefore those indicated, namely V.sub.c =V.sub.c. In order to achieve this, the circuit as it stands must be cycled prior to actual operation to establish the correct working voltages. However, capacitor C will not hold its charge indefinitely and V.sub.c will slowly decay from V.sub.c to V.sub.1 due to leakage resistance. Typical leakages allow V.sub.c to be held for up to 100 ms without problem.

Detailed Description Text (11):
To avoid droop, the circuit of FIG. 1 must be modified to take an additional power supply which acts as an initiating charge means and is capable of supplying the full peak voltage V.sub.c to capacitor C. This modification is sketched in FIG. 3, in which a supply voltage V.sub.3 equal in magnitude to peak voltage VC is connected to capacitor C via a switch S.sub.6. Switch S.sub.6 is kept on when all other switches are off, that is, between pulse sequences and ensures that the requisite electrical energy is stored in capacitor C to establish the required current flow in coil L when desired. As soon as current is required through coil L, S.sub.6 is switched off, S.sub.5 is switched on and the bridge is activated. Discharge of capacitor C through the bridge immediately establishes the required magnitude of current flow in coil L. Once current is established, the operations continue as previously described. On final switch off, V.sub.3 is again coupled to capacitor C via switch S.sub.6.

Detailed Description Text (12):
The fact that S.sub.1 to S.sub.4 are initially all off means that the load on supply V.sub.1 changes and voltage V.sub.A varies. This may be obviated by adding a third arm to the bridge of FIG. 1. This comprises a switched load connected between terminal T.sub.1 and earth which is normally off. However, when no current through coil L is required, the third arm shunts current through diode D.sub.6 to earth thereby holding V.sub.A constant.

Detailed Description Text (13):
In the FIG. 1 circuit the bridge configuration is shown as comprising four switches. Two of these switches, for example switches S.sub.2 and S.sub.4, may be replaced by pairs of terminals for connection to individual current supply sources which replace source V.sub.1. A duplicate of capacitor C and its associated switch S.sub.5 and bypass diode D.sub.5 is connected to the opposite end of the bridge to switch S.sub.5 and point A or B is earthed instead of terminal T.sub.2. Diodes are also included at each end of the bridge.

Detailed Description Text (14):
In the circuit described in FIG. 1 the magnitude of the forward and reverse currents are equal. However, in some NMR applications, unequal magnitudes of current are required. The basic principles of switching described above can be adapted to this situation as indicated in FIG. 4.

Detailed Description Text (15):
In the circuit shown in FIG. 4 like parts have like references to FIG. 1 but in FIG. 4 the two arms of the bridge comprising the switches S.sub.1 and S.sub.2 are taken to two different current supply terminals T.sub.1 and T.sub.3 supplied from voltage sources V.sub.1 and V.sub.4 of different magnitudes. Separate capacitors C.sub.1 and C.sub.2 are connected to terminals T.sub.1 and T.sub.3 through switches S.sub.5 and S.sub.8 respectively. Terminal T.sub.1 is connected to capacitor C.sub.2 through a diode D.sub.8 and terminal T.sub.3 is connected to capacitor C.sub.1 through a diode D.sub.5 shunted by diodes D.sub.5 and D.sub.8. Capacitor C.sub.1 is trickle charged from a voltage source V.sub.2 through a protective diode D.sub.7 and resistor R.sub.1. Capacitor C.sub.2 is tricle charged from a voltage source V.sub.6 through a protective diode D.sub.10 and resistor R.sub.2.

Detailed Description Text (16):
Let an initial current I.sub.1 flow through switch S.sub.1, coil L and switch S.sub.4. On turn-off of switches S.sub.1 and S.sub.4 capacitor C.sub.1 charges, storing the initial energy 1/2LI.sub.1.sup.2. The reverse current I.sub.2.noteq.I1 then flows through switch S.sub.2, L and switch S.sub.3 with appropriate gating, provided that the energy equivalent of 1/2LI.sub.2.sup.2 was previously stored on the capacitor C.sub.2.

Detailed Description Text (18):

In order to present roughly constant loads to the two power supplies, V.sub.1 and V.sub.2, each half of the bridge, i.e. S.sub.1, S.sub.3 and S.sub.2, S.sub.4 can be shunted by additional current switches from both D.sub.6 and D.sub.9 to earth.

Detailed Description Text (19):
The circuits described are capable of producing a variety of useful current waveforms. One example is a trapezoidal like burst of equal amplitude positive and negative currents with periods .tau..sub.1 and .tau..sub.2, see FIG. 5(a). A similar current waveform with unequal positive and negative currents is shown in FIG. 5(b). Since the circuits actually switch off at a zero-crossing, time delays P.sub.1 and P.sub.2 may be interposed as indicated in FIG. 5(c).

Detailed Description Text (21):
Arrangements for energy storage using capacitors have been described above. This is convenient since tuned circuits naturally interconvert between magnetic and electrostatic energy. In practice equations (8) and (9) dictate the storage capacitance and the peak voltage. Assuming the components can withstand this voltage, there is still the problem of top-up provided by the supply V.sub.2 in FIG. 1, and the initiating charge provided by V.sub.3 in FIG. 3. Both arrangements require relatively high voltage power supplies and in the case of V.sub.2, the current drains can be significant. For one shot waveforms there is no problem. But with repeating waveforms, as used in EPI, HT (high tension) or even EHT (extra high tension) power supplies may be required.

Detailed Description Text (22):
An attractive and alternative approach is to use the capacitor C as a short term energy store, transferring the energy to another storage inductance, L', placed well away from the primary coil L. A circuit arrangement is shown in FIG. 6 using two bridges and two low voltage power supplies V.sub.1 and V.sub.1 '. If L=L' then V.sub.1 .perspectiveto.V.sub.1 '. Losses in the system are made up by passing extra current through L'. The losses referred to arise from power dissipation in the diodes and switches. Long term losses in the inductance (I.sup.2 r) are made up from the power supply. In a superconductive coil, these are zero. Thus once the current I is achieved in L or L' the current would be maintained with no power consumption. Note that in this arrangement, capacitor C can be small. The rise time would be limited purely by the voltage capabilities of the switches and diodes. The storage capacitor is required to hold charge for only a short time and no top-up voltage source or high voltage start-up supply is required.

Detailed Description Text (23):
Although a four element bridge for storage coil L' strictly speaking, is not required, the arrangement of FIG. 6 provides a more or less constant load for supply V.sub.1 '. As in the previous circuits, the bridge for coil L should be shunted with a third arm to provide a current drain on V.sub.1 when all four switch elements of that bridge are off.

Detailed Description Text (24):
An alternative circuit is shown in FIG. 7. In this arrangement as in FIG. 1 energy is momentarily stored in capacitor C when reversing the current direction through L. However, when it is desired to switch off all four switches S.sub.1 to S.sub.4, the magnetic energy 1/2LI.sup.2 in coil L is first transferred to coil L' via switch S.sub.9. Current through S.sub.9 is controlled by a current regulator CR. The current flow through coil L' and its energy 1/2L'I'.sup.2 in coil L' is then maintained from the same supply V. A short time before current flow in coil L is required switch S.sub.g is opened and the energy in coil L' is dumped into capacitor C thus providing the necessary initial condition for start-up. This means that the current drain is fairly constant thus avoiding transient problems in the low voltage power supply. No HT or EHT top-up supplies are needed in this arrangement.

Detailed Description Text (25):
The various switches referred to can be bidirectional mechanical devices, bidirectional solid-state devices, e.g. FET's, standard high power transistors, SCR's, unidirectional vacuum tubes or gas filled thyratrons. All can be made to function with appropriate driving circuitry. Naturally for high speed operation, mechanical switches are not as useful.

Detailed Description Text (26):
A practical circuit based on FIG. 1 is shown in FIG. 8. Power FET's (HEXFETS IRF130) are used as the switches S.sub.1 to S.sub.5, the integral body diode of these devices

being employed for the return current paths.

Detailed Description Text (27):
A switching time t.sub.s of 50 .mu.s was chosen in order to keep the peak capacitor voltage below the device limit of 100 V using equations (8) and (9). A capacitor of 10 .mu.F satisfies the requirements.

Detailed Description Text (28):
Switch S.sub.5 is arranged to open between transitions after the current has settled (i.e. 2t.sub.s after the last transition) to enable the capacitor voltage to be topped up to V.sub.2 as described earlier and shown in FIG. 2(a). This switch closes during a transition, when energy is being transferred into C via S.sub.5 's body diode or via S.sub.5 itself when it has closed, and S.sub.5 remains closed until the stored energy in C has been returned to the coil at time t=2t.sub.s.

Detailed Description Text (30):
In this arrangement there is no requirement for instantaneous switching or simultaneous switching of any of the devices. Also, there is always a current path in circuit with coil L, either via the devices or the diodes during transitions thus minimising the possibility of `glitches`.

Detailed Description Text (31):
Series/parallel combinations of devices can be used for higher voltages and currents and for shorter transition times.

Detailed Description Text (32):
The circuit of FIG. 8 has been used to switch a current of 20 A through a coil L of 100 .mu.H with a switching time t.sub.s of 50 .mu.s.

Detailed Description Text (33):
More powerful switches, e.g. SCR's can be used to handle very high voltages and currents (.about.4 kV and 1000 Amps). Suitable snubber circuits may be introduced between the anodes and cathodes of the SCR's in order to prevent their retriggering.

CLAIMS:

1. An inductive circuit arrangement comprising:

four switches connected to form four arms of a bridge configuration,

current supply terminals at opposite ends of the bridge,

inductive coil means connected across the bridge so that current can flow in either direction through the coil means depending on the setting of the switches,

a series connection of capacitor means and a series switch connected across the supply terminals, and

means for operating said four switches and said series switch so as to connect the capacitor means across the coil means at least for a sufficient period of time until the current flow through the coil reduces to zero by charging of the capacitor means and so as to isolate said capacitor means from the bridge configuration to enable current to continue to flow through the coil.

2. The arrangement as claimed in claim 1 in which the said switches are shunted by unidirectional current flow devices.

3. The arrangement as claimed in claim 1 in which the said means for operating the switches functions subsequently to the reduction of the current flow through the coil to zero to allow the capacitor means to discharge to generate current flow through the coil means in the opposite direction to the current flow in one direction.

4. The arrangement as claimed in claim 3 in which there is provided trickle charge means connected to the capacitor means to enable the capacitor means to be charged to a predetermined voltage value after discharge.

6. The arrangement as claimed in claim 1 in which a unidirectional current flow device is connected in series with the current supply terminals to prevent flow of current through the current supply terminals in the reverse direction.

7. The arrangement as claimed in claim 1 in which initiating charge means is connected through a further switch to initially charge the capacitor means to a peak voltage to provide the requisite electrical energy to establish a required current flow in the said coil means.

8. The arrangement as claimed in claim 1 in which there is provided a switched parallel path accross the bridge to maintain a substantially constant value of current through the current supply terminals irrespective of the settings of the switches in the bridge configuration.

9. The arrangement as claimed in claim 1 in which the two arms of the bridge at one end thereof are connected to respective current supply terminals each at different voltage levels to enable different values of current flow to be established through the coil means in respective opposite directions.

10. The arrangement as claimed in claim 9 in which separate series connections each of a capacitor means and a switch are connected to said respective current supply terminals.

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**Search Results -** Record(s) 1 through 13 of 13 returned.

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☐ 1. Document ID: US 20020183638 A1

L32: Entry 1 of 13 File: PGPB Dec 5, 2002

PGPUB-DOCUMENT-NUMBER: 20020183638
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020183638 A1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

PUBLICATION-DATE: December 5, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
| Swanson, David K. | Mountain View | CA | US | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw. Desc | Image

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☐ 2. Document ID: US 20020147470 A1

L32: Entry 2 of 13 File: PGPB Oct 10, 2002

PGPUB-DOCUMENT-NUMBER: 20020147470
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020147470 A1

TITLE: Electromagnetic interference immune tissue invasive system

PUBLICATION-DATE: October 10, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
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| Miller, Victor | Clarence | NY | US | |

US-CL-CURRENT: 607/9

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw. Desc | Image

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## 3. Document ID: US 20020143258 A1

L32: Entry 3 of 13 File: PGPB Oct 3, 2002

PGPUB-DOCUMENT-NUMBER: 20020143258
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20020143258 A1

TITLE: Electromagnetic interference immune tissue invasive system

PUBLICATION-DATE: October 3, 2002

INVENTOR-INFORMATION:

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| Miller, Victor | Clarence | NY | US | |

US-CL-CURRENT: 600/476

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

## 4. Document ID: US 20010012918 A1

L32: Entry 4 of 13 File: PGPB Aug 9, 2001

PGPUB-DOCUMENT-NUMBER: 20010012918
PGPUB-FILING-TYPE: new
DOCUMENT-IDENTIFIER: US 20010012918 A1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

PUBLICATION-DATE: August 9, 2001

INVENTOR-INFORMATION:

| NAME | CITY | STATE | COUNTRY | RULE-47 |
|---|---|---|---|---|
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US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

## 5. Document ID: US 6428537 B1

L32: Entry 5 of 13 File: USPT Aug 6, 2002

US-PAT-NO: 6428537
DOCUMENT-IDENTIFIER: US 6428537 B1

TITLE: Electrophysiological treatment methods and apparatus employing high voltage pulse to render tissue temporarily unresponsive

DATE-ISSUED: August 6, 2002

INVENTOR-INFORMATION:

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US-CL-CURRENT: 606/41; 607/122

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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6. Document ID: US 6421556 B2

L32: Entry 6 of 13 File: USPT Jul 16, 2002

US-PAT-NO: 6421556
DOCUMENT-IDENTIFIER: US 6421556 B2

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: July 16, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
|---|---|---|---|---|
| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 600/510

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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7. Document ID: US 6369465 B1

L32: Entry 7 of 13 File: USPT Apr 9, 2002

US-PAT-NO: 6369465
DOCUMENT-IDENTIFIER: US 6369465 B1
**** See image for Certificate of Correction ****

TITLE: Power supply for use in electrophysiological apparatus employing high-voltage pulses to render tissue temporarily unresponsive

DATE-ISSUED: April 9, 2002

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
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| Swanson; David K. | Mountain View | CA | | |

US-CL-CURRENT: 307/112; 307/115

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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8. Document ID: US 6212426 B1

L32: Entry 8 of 13 File: USPT Apr 3, 2001

US-PAT-NO: 6212426
DOCUMENT-IDENTIFIER: US 6212426 B1

TITLE: Systems and methods for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: April 3, 2001

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
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US-CL-CURRENT: 600/510; 606/34

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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9. Document ID: US 6107699 A

L32: Entry 9 of 13 File: USPT Aug 22, 2000

US-PAT-NO: 6107699
DOCUMENT-IDENTIFIER: US 6107699 A

TITLE: Power supply for use in electrophysiological apparatus employing high-voltage pulses to render tissue temporarily unresponsive

DATE-ISSUED: August 22, 2000

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
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US-CL-CURRENT: 307/112; 307/115

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

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10. Document ID: US 6023638 A

L32: Entry 10 of 13 File: USPT Feb 8, 2000

US-PAT-NO: 6023638
DOCUMENT-IDENTIFIER: US 6023638 A

TITLE: System and method for conducting electrophysiological testing using high-voltage energy pulses to stun tissue

DATE-ISSUED: February 8, 2000

INVENTOR-INFORMATION:

| NAME | CITY | STATE | ZIP CODE | COUNTRY |
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US-CL-CURRENT: 600/510; 606/41

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

## 11. Document ID: US 5684402 A

L32: Entry 11 of 13 File: USPT Nov 4, 1997

US-PAT-NO: 5684402
DOCUMENT-IDENTIFIER: US 5684402 A
**** See image for Certificate of Correction ****

TITLE: Gradient coil power supply and imaging method

DATE-ISSUED: November 4, 1997

INVENTOR-INFORMATION:

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| Evans; Robert R. | Framingham | MA | | |

US-CL-CURRENT: 324/322; 324/318

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
Draw Desc | Image

## 12. Document ID: US 5521507 A

L32: Entry 12 of 13 File: USPT May 28, 1996

US-PAT-NO: 5521507
DOCUMENT-IDENTIFIER: US 5521507 A

TITLE: Gradient coil power supply and imaging method

DATE-ISSUED: May 28, 1996

INVENTOR-INFORMATION:

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US-CL-CURRENT: 324/322; 324/318

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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## 13. Document ID: US 4820986 A

L32: Entry 13 of 13 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

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US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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|---|---|
| SWITCH$4 | 0 |
| SWITCH | 1425700 |
| SWITCHA | 10 |
| SWITCHABE | 2 |
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| SWITCHABLE | 33326 |
| SWITCHABLY | 4999 |
| SWITCHADS | 3 |
| SWITCHAING | 1 |
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L32: Entry 11 of 13 File: USPT Nov 4, 1997

DOCUMENT-IDENTIFIER: US 5684402 A
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TITLE: Gradient coil power supply and imaging method

Abstract Text (1):
In a magnetic resonance imaging system in which the read and phase directions are rotated with respect to the orthogonal gradient coil directions, a gradient coil is driven to generate a gradient waveform having a segment, either sinusoidal or linear, that approximates the sum of the simultaneous non-zero components of the read and phase gradient waveforms in the direction of the gradient coil. Resonant circuits, each including a gradient coil, generate simultaneous periodic gradient coil waveforms in which the integral over each waveform period is non-zero. First and second capacitive elements in the resonant power supply are electrically connected to the gradient coil through a switch and a bridged network, respectively. The bridged network selectively provides current flow paths between the coil and either of the terminals of the second capacitive element.

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Brief Summary Text (2):
This invention relates to producing modulated gradient fields in magnetic resonance imaging (MRI) systems.

Brief Summary Text (3):
In a typical MRI system, three electromagnetic gradient coils are driven using respective power supplies to generate magnetic field gradients in each of three orthogonal (e.g., x, y, and z) directions, termed "gradient coil directions." The magnetic fields generated by the gradient coils generally have components parallel to the direction of a main magnetic field, where the strengths of the components vary spatially (e.g., linearly) in each of the respective gradient coil directions. The gradient coils are typically driven to generate "read," "phase," and "slice" gradient waveforms, where the plane or cross-section to be imaged lies parallel to the plane defined by the directions of the read and phase gradients.

Brief Summary Text (4):
A variety of gradient coil power supplies are known for generating magnetic field gradients for MRI systems. In some systems, the power supply consists only of an amplifier, which drives the gradient coil directly to produce the desired gradient waveforms. The amplifiers can be controlled to obtain images of planes that lie at oblique angles to the gradient coil directions.

Brief Summary Text (5):
In other MRI systems, such as those disclosed in Rzedzian U.S. Pat. No. 4,628,264, incorporated herein by reference in its entirety, the gradient coil is connected in parallel with a capacitor to form a parallel resonant circuit. And in still other MRI power supplies, such as those disclosed in Rzedzian et al. U.S. Pat. No. 5,285,161, incorporated herein by reference in its entirety, the gradient coil is connected in series with a capacitor to form a series resonant circuit. In both the parallel and the series resonant power supplies, an amplifier drives the coil-capacitor circuit at or near its resonant frequency, generating a sinusoidally varying gradient waveform. The power supplies can be controlled to interrupt the resonant sinusoidal waveform for

periods of arbitrary duration.

Brief Summary Text (7):
In one general aspect of the invention, the read and phase directions are rotated with respect to the gradient coil directions. One of the gradient coils is driven to generate a gradient waveform having a segment, either sinusoidal or linear, that approximates the sum of the simultaneous non-zero components of the read and phase gradient waveforms in the direction of the gradient coil.

Brief Summary Text (8):
Among other advantages, this aspect of the invention allows the read-phase plane, that is, the clinical imaging (or scan) plane, to be rotated through one or more angles with respect to the gradient coil directions. Thus, an object in which the cross-section of interest does not lie perpendicular to any of the x, y, or z gradient coil axes need not by physically rotated in order to obtain a satisfactory image. Rather, the image plane itself can be rotated as necessary to obtain an image of the desired slice of the object.

Brief Summary Text (9):
Moreover, because the non-zero components of the read and phase gradient waveforms are generated simultaneously, for given gradient waveform frequencies and amplitudes the total time needed to sample a single image is shorter than if the non-zero components were generated sequentially.

Brief Summary Text (10):
In preferred embodiments, all three of the gradient coils are driven using resonant power supplies to generate periodic waveforms that approximate the summed components of the read and phase gradient waveforms in each of the x, y, and z gradient coil directions. In particular, the integral over one period of each gradient coil waveform equals the integral over the same period of the summed components of the read and phase gradient waveforms in the direction of that waveform. Each power supply includes two capacitive elements that are precharged prior to the initiation of the gradient waveforms to generate sinusoidal resonances at desired amplitudes when switches connecting the respective capacitive elements to the coils are closed. In operation, one of the two switches is opened (e.g., after a half-period sinusoidal segment has been generated) at substantially the same time that the other switch is closed.

Brief Summary Text (11):
In another aspect of the invention, a plurality of resonant circuits, each including a gradient coil, are driven to generate simultaneous periodic gradient waveforms in which the integral over each waveform period is non-zero.

Brief Summary Text (12):
Among other advantages of this aspect of the invention, the resonant circuits can be driven at their respective resonant frequencies, reducing the amount of power necessary to produce a gradient waveform of a desired amplitude (e.g., a DC-offset sinusoidal waveform or a waveform comprised of sinusoidal segments).

Brief Summary Text (13):
Another aspect of the invention includes a resonant power supply in which first and second capacitive elements are electrically connected to the gradient coil through a switch and a bridged network, respectively. The bridged network selectively provides current flow paths between the coil and either of the terminals of the second capacitive element.

Brief Summary Text (14):
In preferred embodiments, a controller controls the switch and the bridge in accordance with a predetermined, periodic pattern. The bridge includes four bipolar switches, two connected to one terminal of the second capacitive element, and two connected to the other. An amplifier connected to the coil drives the coil with a voltage signal synchronized to the gradient waveform.

Drawing Description Text (2):
FIG. 1 is a cross-sectional, diagrammatic view of an arrangement of MRI coils around a subject body.

Drawing Description Text (5):
FIG. 3 is a timing diagram showing signals used in an echo planar imaging (EPI) MRI sequence.

Drawing Description Text (7):
FIG. 4b is a detail view of one portion of one of the signals of FIG. 4a.

Drawing Description Text (9):
FIG. 5b is a detail view of one portion of one of the signals of FIG. 5a, and showing a switch control sequence for the structure depicted in FIG. 2a.

Drawing Description Text (10):
FIG. 5c is a detail view showing the difference between the current signal shown in FIG. 5b and the current signal shown in FIG. 4b.

Drawing Description Text (12):
FIG. 6b is a detail view of one portion of one of the signals of FIG. 6a, and showing a switch control sequence for the structure depicted in FIG. 2a.

Drawing Description Text (13):
FIG. 7 is a timing diagram showing signals used in another EPI MRI sequence.

Drawing Description Text (15):
FIG. 8b is a detail view of one portion of one of the signals of FIG. 8a, and showing a switch control sequence for the structure depicted in FIG. 2a.

Drawing Description Text (19):
FIG. 10b is a detail view of one portion of one of the signals of FIG. 10a.

Detailed Description Text (2):
With reference to FIG. 1, magnetic coils 10 are oriented in relation to orthogonal x, y, and z axes. As described in U.S. Pat. No. 4,628,264 to Rzedzian, incorporated herein in its entirety by reference, a whole-body coil 12 generates a static main magnetic field, and gradient coils 14, 15, 16 (shown diagrammatically) provide magnetic field gradients G.sub.x, G.sub.y, and G.sub.z in the respective x, y, and z gradient coil directions. Coils 10 surround subject body 18. A separate resonant power supply (RPS) 20, 21, 23 drives each of gradient coils 14, 15, 16.

Detailed Description Text (3):
A topology for RPS 20 for driving gradient coil 14 is shown in FIG. 2a. RPS 20 includes a controllable gradient amplifier 22, such as a linear amplifier or a switching amplifier, in series with gradient coil 14 and two bridged capacitor networks 24a, 24b. Each bridged capacitor network 24a, 24b includes four switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d, a capacitor 30a, 30b, and an associated charging circuit 32a, 32b. Switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d may be bipolar switches, such as insulated gate bipolar transistors (IGBTs), or unipolar switches such as silicon controlled rectifiers arranged in pairs. A suitable charging circuit 32a, 32b is described in U.S. Pat. No. 5,245,287 to Rzedzian, incorporated herein in its entirety by reference. Alternatively, a single charging circuit that can be switched between capacitors 30a, 30b can be substituted for charging circuits 32a, 32b, or capacitors 30a, 30b can be charged directly from amplifier 22. A run/charge controller 33 asserts control signals for controlling the state of switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d, and also controls the operation of chargers 32a, 32b and amplifier 22. In order to accommodate transients in the voltage signal supplied by amplifier 22 when switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d are opened and closed by controller 33, it may be necessary to include additional switches and snubbers (not shown) in RPS 20.

Detailed Description Text (4):
RPSs 21, 23, for driving gradient coils 15, 16, are identical to RPS 20, and are similarly controlled.

Detailed Description Text (5):
An alternate RPS 35 is shown in FIG. 2b. (For convenience and clarity, many of the numerals used in FIG. 2a are used to identify also the principle components and subassemblies in FIG. 2b, as well as in the other alternate RPS embodiments shown and described herein.) RPS 35 is identical to RPS 20, except switches 26b, 26c have been eliminated, and switch 26d has been replaced with a permanently conducting section.

Detailed Description Text (6):
As disclosed in Rzedzian U.S. Pat. No. 4,940,941; incorporated herein by reference in its entirety, and also with reference to FIG. 3, echo planar imaging (EPI), known in the prior art, involves the generation of gradient waveforms in orthogonal read, phase,

and slice directions. A gradient waveform is a representation of how the strength of a magnetic field gradient (e.g., in units of gauss/cm) varies with time. For each gradient coil 14, 15, 16, there is a direct relationship between the strength of the magnetic field gradient and the magnitude of the current signal supplied to the gradient coil. Thus, if the read, phase, and slice directions are parallel to the x, y, and z gradient coil directions, the respective current signals used to drive gradient coils 14, 15, 16 will generally have the same shapes as the gradient waveforms shown in FIG. 3, although the relative amplitudes of the current signals need not be (and in general will not be) identical to the relative amplitudes of the gradient waveforms.

Detailed Description Text (7):
In EPI, as well as in some other imaging techniques, a slice-select gradient 34 (e.g., a square or trapezoidal pulse of amplitude I.sub.s) is first generated in the slice direction, followed by pre-phasing gradient pulses 36, 38 in the read and phase directions and, optionally, a refocus gradient pulse 40 in the slice direction.

Detailed Description Text (8):
The acquisition sequence, which follows the above pulse sequence, includes a read-out gradient waveform 42 in the read direction and a phase-coding gradient waveform 44 in the phase direction. Read-out gradient waveform 42 is a sinusoid of amplitude I.sub.r :

Detailed Description Text (9):
Phase-coding gradient waveform 44 is a series of positive, relatively high-frequency cosine "blips" of amplitude I.sub.p centered around the zero-crossings 46 (both positive-going and negative-going) of read-out gradient waveform 42:

Detailed Description Text (10):
where T.sub.r equals .pi./.omega..sub.r, one-half of the period of the read-out gradient waveform, and T.sub.p equals .pi./.omega..sub.p, one-half of the period of the phase-coding gradient waveform. Alternatively, the blips of phase-coding gradient waveform 44 could be negative.

Detailed Description Text (11):
Slice-select gradient pulse 38, together with a simultaneously generated radio-frequency (RF) excitation pulse, excite the nuclei (not shown) in a planar slice of subject body 18. The axial location of this planar slice, which lies perpendicular to the slice direction, is determined by the frequency of the RF excitation pulse. To generate an image, read-out gradient waveform 34 and phase-coding gradient waveform 36 are then employed to evaluate the spatially varying density of the excited nuclei in the selected slice. Thus, slice-select gradient pulse 38 determines the cross-section of subject body 18 (i.e., the image plane) that is imaged. Accordingly, if gradient coils 14, 15, 16 are driven to generate the gradient waveforms depicted in FIG. 3, the image plane will be perpendicular whichever of the x-, y-, or z-axis gradient coils 14, 15, 16 is used to generate slice-select gradient 38.

Detailed Description Text (12):
In many situations, it is desirable to image an object, e.g., an organ such as a human heart, in which the cross-section of interest is not perpendicular to, and cannot conveniently be physically rotated to an orientation perpendicular to, the x, y, or z axes of coils 10. In such instances it is advantageous to rotate instead the image plane, as determined by the orthogonal read, phase, and slice directions, to the desired orientation. To accomplish this using EPI techniques, the read, phase, and slice gradient waveforms shown in FIG. 3 are generated in orthogonal read, phase, and slice directions that are rotated through at least one non-zero angle with respect to the x, y, and z gradient coil directions. Because of this rotation, each of the desired read, phase, and slice waveforms has components in at least one of the x, y, and z gradient coil directions. Thus, as described in greater detail below, the image plane can be rotated by driving gradient coils 14, 15, 16 to generate gradient waveforms that equal or approximate the sums of those components of the read, phase, and slice gradient waveforms that lie in the respective x, y, and z gradient coil directions.

Detailed Description Text (13):
The rotation of any orthogonal cartesian set of axes with respect to a given frame of reference can be described by three angles, .theta., .phi., and .psi.. Known as Euler angles, .theta. and .phi. are the polar and azimuthal angles, respectively, and .psi. represents the rotational orientation of the image in the image plane. Thus, .theta. and .phi. determine the orientation of the slice plane with respect to the x, y, and z axes, and .psi. determines the orientation of the displayed MRI image of that slice

plane.

Detailed Description Text (14):
For a given set of Euler angles, the rotation from the desired read, phase, and slice directions to the x, y, and z axes of coils 10 is described by the following relation: ##EQU1## where: ##EQU2##

Detailed Description Text (15):
Thus, during the slice-select phase, when I.sub.r and I.sub.p both equal zero, slice-select gradient pulse 38 of amplitude I.sub.s is generated in the desired rotated slice direction when:

Detailed Description Text (16):
Pre-phasing gradient pulses 36, 38 and refocus pulse 40 are generated in the rotated directions in a similar manner.

Detailed Description Text (17):
During the acquisition sequence, when I.sub.s equals zero, the desired read-out and phase-coding gradients are generated in the desired rotated read and phase directions when:

Detailed Description Text (19):
Thus, in order to generate the read, phase, and slice gradient waveforms shown in FIG. 3 in a desired rotated frame of reference, the desired angles of rotation .theta., .phi., and .psi. are substituted into equations (4), (8), and (9). For instance, in order to generate the EPI read, phase, and slice gradient waveforms in a frame of reference that is rotated through 30.degree. and 75.degree. with respect to the x, y, and z axes, the x, y, and z gradient coils 14, 15, 16 can be driven with the current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) shown in FIG. 4a. Current signal I.sub.x (t), together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 4b.

Detailed Description Text (20):
The pure sinusoidal portion of the desired waveform (i.e., the portion described by equation (8)) is generated, as described in greater detail below, using bridged capacitor network 24a. Capacitor 30a and coil 14 provide a circuit having a resonant frequency of .omega..sub.r when: ##EQU3## where L is the inductance of gradient coil 14 and C.sub.1 is the capacitance of capacitor 30a. Because L and .omega..sub.r are generally given, capacitor 30a should thus be selected such that:

Detailed Description Text (21):
The capacitors for the first bridged capacitor networks of the resonant power supplies of the other two gradient coils 15, 16 are likewise chosen to provide a circuit having a resonant frequency of .omega..sub.r.

Detailed Description Text (22):
To avoid transients, prior to initiating a gradient waveform readout sequence, capacitor 30a is precharged to an initial voltage V.sub.1i equal to the peak capacitor voltage generated when gradient coil 14 resonates with the desired coil current I.sub.r a.sub.ri, as provided by equation (8). As described in U.S. Pat. No. 5,285,161 issued to Rzedzian et al.: ##EQU4##

Detailed Description Text (23):
The summed portion of the desired waveform (i.e., the portion described by equation (9)) can be approximated by a half-period phase-offset cosine segment having the same frequency .omega..sub.p as the phase blips of phase gradient 36. For the negative-going portion of the gradient waveform, this segment is described by:

Detailed Description Text (24):
For the positive-going portion of the gradient waveform, the segment is described by:

Detailed Description Text (25):
The phase-offset cosine segment of the desired generalized waveform is generated, as described in greater detail below, by employing bridged capacitor network 24b. The capacitance C.sub.2 of capacitor 30b is chosen to provide the desired frequency .omega..sub.p :

Detailed Description Text (26):
The capacitors for the-second bridged capacitor networks of the resonant power supplies

of the other two gradient coils 15, 16 are likewise chosen to provide a circuit having a resonant frequency of .omega..sub.p.

Detailed Description Text (27):
The amplitude I.sub.2i of the phase-offset cosine segment should be such that the integral over this segment equals the integral over one segment of the summed portion of the desired waveform. Accordingly: ##EQU5## Note that the integrals of the phase-offset cosine segments described by equations (13) and (14) are both positive.

Detailed Description Text (28):
The values of I.sub.r and I.sub.p are derived from imaging requirements: ##EQU6## Where .gamma. is the gyromagnetic ratio, ff is the strength of the gradient coil, .DELTA. is the image resolution, and FOV is the field of view (here, in the phase direction).

Detailed Description Text (29):
The current waveform of coil 14 should be continuous everywhere, including at the point of transition between the pure sinusoidal portion and the phase-offset cosine segment. At this point t.sub.i, which occurs T.sub.p /2 before each zero-crossing 40, equation (8) thus equals equation (13): ##EQU7## Noting that t.sub.i modT.sub.r equals -T.sub.p /2, one-quarter of the period of phase blip 36, this expression can be rearranged to find .eta..sub.i : ##EQU8##

Detailed Description Text (30):
Using .eta..sub.i, the amplitude I.sub.2i of the half-period, phase-offset cosine segment can be determined from equation (16). These values, together with the relationship ##EQU9## can then be used to calculate the initial precharge voltage V.sub.2i on capacitor 30b that provides the desired phase offset .eta..sub.i : ##EQU10##

Detailed Description Text (31):
The current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) used to drive the x, y, and z gradient coils 14, 15, 16 in order to generate the EPI read, phase, and slice gradient waveforms shown in FIG. 3 in a frame of reference that is rotated through (for example) 30.degree. and 75.degree. with respect to the x, y, and z axes are shown in FIG. 5a. In short, based on imaging requirements, controller 33 determines the desired read, phase, and slice waveforms in the respective read, phase, and slice directions. From these desired waveforms, controller 33 performs the appropriate transforms to determine the precharge voltages on capacitors 30a, 30b, as well as the current waveform to be provided by amplifier 22. As shown in FIG. 5b and described below, controller 33 controls switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d to cause RPS 20 to generate gradient field waveforms that approximate the summed x, y, and z components of the desired read, phase, and slice waveforms.

Detailed Description Text (32):
The slice-select, pre-encode, and refocus pulses 34, 36, 38 are generated by driving gradient coils 14, 15, 16 directly with their respective gradient amplifiers to generate current pulses of the appropriate amplitude. Thus, for example, during the slice-select period, only switches 26a, 26b in RPS 20 are closed, and gradient amplifier 22 is controlled to supply the requisite current pulse of amplitude I.sub.s a.sub.sx, as provided by equation (5).

Detailed Description Text (33):
Current signal I.sub.x (t) from FIG. 5a, together with its corresponding voltage signal V.sub.x (t) and the switch control sequence for RPS 20, are shown in detail in FIG. 5b.

Detailed Description Text (34):
Prior to initiating the acquisition sequence, capacitors 30a, 30b are precharged to precharge voltages V.sub.1i, V.sub.2i. Once capacitors 30a, 30b have been charged, run/charge controller 33 initiates the acquisition sequence at t.sub.0 by asserting control signals to close switches 26a, 26d (for the embodiment shown in FIG. 2b, controller 33 closes switch 26a). Capacitor 30a then begins to discharge into gradient coil 14, causing gradient coil 14 to generate a gradient waveform segment having frequency .omega..sub.r.

Detailed Description Text (35):
Gradient amplifier 22, which is synchronized to the phase and frequency of the gradient waveform by controller 33, e.g., by monitoring the current of coil 14 and comparing the sensed current to the stored representative waveform determined by controller 33,

provides energy to the resonant system in the form of voltage to compensate for resistive and other parasitic losses in RPS 20.

Detailed Description Text (36):
At time t.sub.1, which occurs T.sub.p /2 before the first zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 26a, 26d, and substantially simultaneously closes switches 28a, 28d. Capacitor 30b then begins to discharge into gradient coil 14, causing gradient coil 14 to generate a gradient waveform having frequency .omega..sub.p. Because of precharge voltage V.sub.2i, the ensuing segment of the gradient waveform is a cosine of amplitude I.sub.2i having a phase-offset .eta..sub.i. Because this is the negative-going portion of the gradient waveform, this phase-shifted cosine is described mathematically by equation (13).

Detailed Description Text (37):
At time t.sub.2, which occurs T.sub.p /2 after the first zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 28a, 28d, and substantially simultaneously closes switches 26a, 26d. Capacitor 30a, the voltage on which has remained essentially constant since t.sub.1, then begins to discharge into gradient coil 14, causing gradient coil 14 to generate another gradient waveform segment having frequency of .omega..sub.r.

Detailed Description Text (38):
At time t.sub.3, which occurs T.sub.p /2 before the next zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 26a, 26d and substantially simultaneously closes switches 28b, 28c. The polarity of capacitor 30b, the voltage on which has remained essentially constant since t.sub.2, is thus reversed in RPS 20 relative to its polarity from t.sub.1 to t.sub.2. Gradient coil 14 again generates a gradient waveform segment having frequency .omega..sub.p. Because this is the positive-going portion of the gradient waveform, the ensuing phase-shifted cosine is described mathematically by equation (14).

Detailed Description Text (39):
At time t.sub.4, which occurs T.sub.p /2 after the next zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 28b, 28c, and substantially simultaneously closes switches 26a, 26d. Capacitor 30a, the voltage on which has remained essentially constant since t.sub.3, then begins to discharge into gradient coil 14, causing gradient coil 14 to generate another gradient waveform segment having a frequency of .omega..sub.r.

Detailed Description Text (40):
This continues until time t.sub.5, which occurs T.sub.p /2 before the next zero crossing 46 of the read-out gradient waveform. At t.sub.5, the cycle described above starting at time t.sub.1 repeats. Thus, the portion between t.sub.1 and t.sub.5 represents one period of the gradient waveform. The duration of this period is 2T.sub.r. Because the integrals of the phase-shifted cosine segments of each period of the waveform are both positive, the integral over one period of the waveform is positive.

Detailed Description Text (41):
As noted, RPS 20 is controlled to approximate the summed portion of the desired waveform (i.e., the portion described by equation (9)) with a half-period phase-offset cosine segment having the same frequency .omega..sub.p as the phase blips of phase gradient 36. The effect of this approximation is demonstrated in FIG. 5c, which shows the difference between the "approximate" x-coil current signal I.sub.x (t) of FIG. 5b and the "ideal" x-coil current signal I.sub.x (t) of FIG. 4b.

Detailed Description Text (42):
Other current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) for approximating the read, phase, and slice gradient waveforms shown in FIG. 3 in a frame of reference that is rotated through, for example, 30.degree. and 75.degree. with respect to the x, y, and z axes are shown in FIG. 6a. Current signal I.sub.x (t), together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 6b.

Detailed Description Text (43):
Referring to FIG. 6b, a single period of a waveform 68 starting at t.sub.1 includes a positive constant-current (and thus also constant-gradient) segment 70 of duration T.sub.h (i.e., t.sub.2 minus t.sub.1), followed at t.sub.2 by a sinusoidal segment 72 of frequency .omega..sub.r, followed at t.sub.3 by a positive horizontal, constant-current segment 74 (i.e., a sinusoidal segment with a frequency equal to zero)

of duration T.sub.h, followed at t.sub.4 by a sinusoidal segment 76 of frequency .omega..sub.r. At t.sub.5, when segment 76 concludes, the waveform repeats. The amplitude of segments 72, 76 is I.sub.r a.sub.ri, and the amplitude I.sub.2i of segments 62, 66 is chosen such that the integral of waveform 68 over each of these segments equals the integral over one segment of the summed portion of the desired waveform, as provided by equation (9): ##EQU11##

Detailed Description Text (45):
RPS 20 is controlled to generate current signal I.sub.x (t), and RPSs 21 and 23 are controlled in a similar manner to generate current signals I.sub.y (t) and I.sub.z (t), respectively. The control sequence to generate waveform 68 is shown in FIG. 6b. Once capacitor 30a has been charged, run/charge controller 33 initiates the acquisition sequence at t.sub.0 by asserting control signals to close switches 26a, 26d. Capacitor 30a then begins to discharge into gradient coil 14, causing gradient coil 14 to generate a segment 78 of gradient waveform 68 having a frequency of .omega..sub.r. On the negative-going portion of segment 78, when (at time t.sub.1) the current of coil 14 equals I.sub.2i, as provided by equation (24), controller 33 opens switches 26a, 26d, and substantially simultaneously closes switches 28a, 28b. Gradient amplifier 22 is then controlled to supply I.sub.2i for a duration of T.sub.p (until time t.sub.2).

Detailed Description Text (46):
At time t.sub.2, controller 33 opens switches 28a, 28b, and substantially simultaneously closes switches 26a, 26d, allowing capacitor 30a, the voltage on which has remained essentially constant since t.sub.1, to resume discharging into gradient coil 14, causing gradient coil 14 to generate segment 72 of gradient waveform 68. On the positive-going portion of segment 72, when (at time t.sub.3) the current of coil 14 equals I.sub.2i, controller 33 opens switches 26a, 26d, and substantially simultaneously closes switches 28a, 28b. Gradient amplifier 22 is again controlled to supply I.sub.2i for a duration of T.sub.p (until time t.sub.4). Segment 76, which concludes at time t.sub.5, is provided in a manner similar to segment 78.

Detailed Description Text (47):
The portion between t.sub.1 and t.sub.5 represents one period of gradient waveform 68. Because the integrals of positive horizontal segments 70, 74 of waveform 68 are positive, the integral over one period of waveform 68 is positive.

Detailed Description Text (48):
The waveform segments between t.sub.1 and t.sub.2 and t.sub.3 and t.sub.4 need not be horizontal segments 70, 74. Rather, amplifier 22 may be controlled during these time periods to generate a variety of different waveform segment shapes (e.g., lines of constant, nonzero slope). At least three factors should be considered when selecting these waveform segments. First, the amplitude and the frequency or frequencies of the waveform should be within the bandwidth of amplifier 22. Because amplifier 22 drives coil 14 directly during these segments, the frequency of the waveform need not be determined with reference to the resonant frequencies of RPS 20. Second, to provide a continuous current waveform, the waveform segments should be continuous with adjacent sinusoidal waveform segments 72, 76, 78. Third, the waveform segments should be chosen so that the integral over each segment equals the integral over the same time period of the summed portion of the desired waveform, as provided by equation (9).

Detailed Description Text (49):
An alternate EPI sequence is shown in FIG. 7. This sequence is similar to that shown in FIG. 3 (having a read-out gradient waveform 55, a phase-coding gradient waveform 57, and a slice-select gradient waveform 59 of amplitudes I.sub.r, I.sub.p, and I.sub.s, respectively), except read-out gradient waveform 55 is equal to zero when phase-coding gradient waveform 57 is nonzero. Accordingly, with the exception of prephasing gradient pulses 61, 63, when any one gradient waveform is nonzero, the other two gradient waveforms are zero.

Detailed Description Text (50):
In order to generate the EPI read, phase, and slice gradient waveforms shown in FIG. 7 in a frame of reference that is rotated, for example, through 30.degree. and 75.degree. with respect to the x, y, and z axes, the x, y, and z gradient coils 14, 15, 16 can be driven with the current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) shown in FIG. 8a. Current signal I.sub.x (t), together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 8b.

Detailed Description Text (51):
Referring to FIG. 8b, a single period 58 of current signal I.sub.x (t) starting at

t.sub.0 includes a positive, half-period sinusoidal segment 60 of frequency .omega..sub.r, followed at t.sub.1 by a positive, half-period sinusoidal segment 62 of frequency .omega..sub.p, followed at t.sub.2 by a negative, half-period sinusoidal segment 64 of frequency .omega..sub.r, followed at t.sub.3 by a positive, half-period sinusoidal segment 66 of frequency .omega..sub.p. At t.sub.4, when segment 66 concludes, the waveform repeats. The amplitude of segments 60, 64 is I.sub.r a.sub.ri, as provided by equation (8), and the amplitude of segments 62, 66 is I.sub.p a.sub.pi, as provided by equation (16), where .eta..sub.i equals zero. Thus, segments 60, 64 are scaled to provide (together with the waveforms on the other two axes) read-out gradient 55 of amplitude I.sub.r in the desired rotated orientation. Similarly, segments 62, 66 are scaled to provide (together with the waveforms on the other two axes) phase-coding gradient 57 of amplitude I.sub.s in the desired rotated orientation. The precharge voltage V.sub.1i on capacitor 30a is given by equation (12). Similarly, the precharge voltage V.sub.2i on capacitor 30b is: ##EQU12##

Detailed Description Text (52):
RPS 20 is controlled to generate current signal I.sub.x (t), and RPSs 21 and 23 are controlled in a similar manner to generate current signals I.sub.y (t) and I.sub.z (t), respectively. The control sequence used to generate waveform 58 is identical to that used to generate the waveform in FIG. 5b. The portion between t.sub.0 and t.sub.4 represents one period of gradient waveform 58. Note that for the same values of .omega..sub.r and .omega..sub.p, a single period of the waveform is longer, by 2T.sub.p, than the waveform. Because the integrals of segments 62, 66 of waveform 58 are positive, the integral over one period of waveform 58 is positive.

Detailed Description Text (53):
Another topology for an RPS 100 for driving gradient coils 14 to provide waveform components of desired waveforms in rotated read, phase, and slice directions is shown in FIG. 9a. Amplifier 22, gradient coil 14, switch 104, and capacitor 30a are all connected in series (the controlling circuitry and the associated control lines are not shown in FIG. 9a). Current source 102, which supplies a constant current I.sub.B, is connected in parallel with capacitor 30a. A charging circuit and a controller (not shown) are provided as described in connection with FIGS. 2a and 2b.

Detailed Description Text (54):
Current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) for approximating the read, phase, and slice gradient waveforms shown in FIG. 3 in a frame of reference that is rotated through, for example, 30.degree. and 75.degree. with respect to the x, y, and z axes are shown in FIG. 10a. Current signal I.sub.x (t) 120 generated by RPS 100, together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 10b. Current signals I.sub.y (t) and I.sub.z (t) are generated by respective power supplies (not shown) that are substantially identical to RPS 100.

Detailed Description Text (55):
Although difficult to see in FIG. 10b, waveform 120, which has a frequency of .omega..sub.r, is positively DC-offset by an amount I.sub.B (and accordingly, the magnitude of voltage signal V.sub.x (t) increases throughout the EPI sequence). The value of I.sub.B is chosen such that the integral over one period of waveform 120 equals the integral, over one period of read-out gradient waveform 42, of phase-coding gradient waveform 44. Thus: ##EQU13##

Detailed Description Text (56):
The precharge voltage V.sub.1i on capacitor 30a is as given above by equation (12). Once capacitor 30a has been charged, the run/charge controller initiates the acquisition sequence at t.sub.0 by asserting control signals to close switch 104. Note that the integral over one period of waveform 120 is positive.

Detailed Description Text (57):
An alternate topology for generating waveforms of the type depicted in FIGS. 10a and 10b is shown in FIG. 9b. RPS 106 is similar to RPS 20 shown in FIG. 2a, except a current source 108 for supplying a constant current I.sub.B has been substituted for bridged capacitor network 24b.

Detailed Description Text (58):
Another topology for an RPS 150 for driving gradient coils 14 to provide waveform components of the desired waveforms in rotated read, phase, and slice directions is shown in FIG. 11 (the controlling circuitry and the associated control lines are not shown in FIG. 11). RPS 150 is similar in construction to RPS 20 shown in FIG. 2a, except bridged capacitor networks 24a, 24b are connected in series in RPS 150, and

switch 152 is connected in parallel with switches 28a, 28b. The operation of RPS 150 is also similar to that of RPS 20. The precharge voltage V.sub.1i on capacitor 30a provided by charger 32a is as given above by equation (12). The pure sinusoidal portion of the desired waveform (i.e., the portion described by equation (8)) is then generated by closing only switches 26a, 26b, 152, and synchronizing amplifier 22 to the current passing through coil 14.

Detailed Description Text (59):
An approximation of the summed portion of the desired waveform (i.e., the portion described by equation (8)) is then generated by opening switch 152 and closing switches 28a, 28d. This connects capacitors 30a, 30b in series with coil 14 and amplifier 22. The effective capacitance C.sub.e of this resonant circuit is: ##EQU14## The capacitance C.sub.1 of capacitor 30a is selected in accordance with equation (11). The desired effective capacitance C.sub.e (and thus also the capacitance C.sub.2 of capacitor 30b) is then found by:

Detailed Description Text (60):
The desired phase offset is provided when capacitor 30b is precharged, by charger 32b, to a precharge voltage V.sub.2i : ##EQU15##

Detailed Description Text (61):
Because capacitor 30a remains in the current flow path to generate the approximation segment, at the conclusion of the segment the charge on the capacitor is not equal to the charge immediately preceding the beginning of the segment. This charge difference can be accommodated through appropriate control of the linear amplifier, charging circuit 32a, or a dedicated charge-correction circuit (comprising, e.g., an additional charged capacitor, not shown, that can be electrically connected in parallel with capacitor 30a at the conclusion of the approximation segment).

Detailed Description Text (62):
Although in the above-described embodiments the three x, y, and z gradient coils 14, 15, 16 are all driven using RPSs 20, 100, 150 or the like, acceptable performance may be realized where only two of the three gradient coils are driven using RPSs 20, 100, 150.

Detailed Description Text (63):
In one example of such an embodiment, the x- and y- axis gradient coils are driven using RPSs 20, 100, 150 or the like, and the z-axis gradient coil is driven directly by a gradient amplifier (not shown). Note from equation (4) that if .psi. is restricted to zero degrees, which constrains the rotation of the displayed MRI image, a.sub.rz also equals zero. Thus, the z-axis gradient coil provides no component of read-out gradient 42 when .psi.=0. During the acquisition period, the z-axis gradient coil provides only a component (I.sub.p a.sub.pz) of phase-coding gradient 44. Because phase-coding gradient 44 generally has a much smaller amplitude (I.sub.p) than read-out gradient 42, this component can be generated by driving the z-axis gradient coil directly with its associated gradient amplifier.

Detailed Description Text (64):
If instead the y- and z-axis gradient coils are driven using RPSs 20, 100, 150 or the like, and the x-axis gradient coil is driven directly by a gradient amplifier (not shown), the x-axis gradient coil provides no component of read-out gradient 42 when: ##EQU16##

Detailed Description Text (65):
And if the y-axis gradient coil is the one that is driven directly by a gradient amplifier (not shown), that gradient coil provides no component of read-out gradient 42 when: ##EQU17##

Detailed Description Text (68):
For instance, the phase blip need not be centered around the zero-crossing of the read out gradient waveform, and need not be a cosine (i.e., a phase-shifted sinusoid). And, as disclosed in Rzedzian U.S. Pat. Nos. 4,628,264 and 5,285,161, the read out gradient waveform can be other than a regular sinusoid, e.g., the read out waveform may be comprised of a series of sinusoidal segments interconnected by horizontal segments. Furthermore, the approximated portion of the summed waveform can be any linear segment (e.g., a straight line at any angle), instead of just a horizontal segment. Thus, the approximation of the summed components of the read and phase gradient waveforms can be either a sinusoidal or a linear segment.

Detailed Description Text (69):
Moreover, although in each of the above-described embodiments the capacitors are connected in series with the gradient coil, they could instead be connected in parallel. And instead of using multiple capacitors to generate different segments of the gradient waveform, the gradient coil could be connected to a capacitor and another inductive coil. The second coil could be switched into and out of the circuit as necessary to generate the desired segments.

CLAIMS:

1. A method of generating a magnetic field for magnetic resonance imaging, said method comprising the steps of:

providing a first resonant circuit including a first capacitive element electrically connected to a first current-carrying gradient coil to provide a first current flow path between said first capacitive element and said first gradient coil for generating a magnetic field gradient waveform;

driving said first resonant circuit to generate a first sinusoidal segment at a first frequency; and

driving said first resonant circuit to generate a second sinusoidal segment at a second frequency different from said first frequency, said second sinusoidal segment being a half-period cosine segment having a non-zero starting phase.

2. The method of claim 1 wherein said first resonant circuit includes a second capacitive element electrically connected to said first current-carrying gradient coil to provide a second current flow path between said second capacitive element and said first gradient coil for generating a magnetic field gradient waveform.

3. The method of claim 1 further comprising the steps of:

providing a second resonant circuit including a second capacitive element electrically connected to a second current-carrying gradient coil to provide a second current flow path between said second capacitive element and said second gradient coil for generating a magnetic field gradient waveform;

driving said second resonant circuit to generate a third sinusoidal segment at a third frequency; and

driving said second resonant circuit to generate a fourth sinusoidal segment at a fourth frequency different from said third frequency, said fourth sinusoidal segment being a half-period phase-offset sinusoidal segment.

4. The method of claim 3 further comprising the steps of:

providing a third resonant circuit including a third capacitive element electrically connected to a third current-carrying gradient coil to provide a third current flow path between said third capacitive element and said third gradient coil for generating a magnetic field gradient waveform;

driving said third resonant circuit to generate a fifth sinusoidal segment at a fifth frequency; and

driving said third resonant circuit to generate a sixth sinusoidal segment at a sixth frequency different from said fifth frequency, said sixth sinusoidal segment being a half-period phase-offset sinusoidal segment.

5. Apparatus for generating a magnetic field for magnetic resonance imaging, said apparatus comprising:

a first resonant circuit including a first capacitive element electrically connected to a first current-carrying gradient coil to provide a first current flow path between said first capacitive element and said first gradient coil for generating a magnetic field gradient waveform;

means for driving said first resonant circuit to generate a first sinusoidal segment at a first frequency; and

means for driving said first resonant circuit to generate a second sinusoidal segment at a second frequency different from said first frequency, said second sinusoidal segment being a half-period cosine segment having a non-zero starting phase.

6. The apparatus of claim 5 wherein said first resonant circuit includes a second capacitive element electrically connected to said first current-carrying gradient coil to provide a second current flow path between said second capacitive element and said first gradient coil for generating a magnetic field gradient waveform.

7. The apparatus of claim 5 further comprising:

a second resonant circuit including a second capacitive element electrically connected to a second current-carrying gradient coil to provide a second current flow path between said second capacitive element and said second gradient coil for generating a magnetic field gradient waveform;

means for driving said second resonant circuit to generate a third sinusoidal segment at a third frequency; and

means for driving said second resonant circuit to generate a fourth sinusoidal segment at a fourth frequency different from said third frequency, said fourth sinusoidal segment being a half-period cosine segment having a non-zero starting phase.

8. The apparatus of claim 7 further comprising:

a third resonant circuit including a third capacitive element electrically connected to a third current-carrying gradient coil to provide a third current flow path between said third capacitive element and said third gradient coil for generating a magnetic field gradient waveform;

means for driving said third resonant circuit to generate a fifth sinusoidal segment at a fifth frequency; and

means for driving said third resonant circuit to generate a sixth sinusoidal segment at a sixth frequency different from said fifth frequency, said sixth sinusoidal segment being a half-period cosine segment having a non-zero starting phase.

9. A method of generating a magnetic field for magnetic resonance imaging, said method comprising the steps of:

providing a resonant circuit including a capacitive element electrically connected to a current-carrying gradient coil to provide a current flow path between said capacitive element and said gradient coil for generating a magnetic field gradient waveform;

driving said resonant circuit to generate a first sinusoidal segment at a first frequency; and

driving said resonant circuit to generate a second sinusoidal segment at a second frequency different from said first frequency immediately after said first sinusoidal segment, said second sinusoidal segment being a half-period cosine segment having a non-zero starting phase.

11. Circuitry for generating a magnetic field in a magnetic resonance imaging system, said circuitry comprising:

a resonant power supply including:

an amplifier;

a current-carrying gradient coil electrically connected to said amplifier;

a first capacitive element electrically connected to said amplifier through a switch, said switch having a closed state in which a first current flow path is provided between said first capacitive element and a first terminal of said amplifier, and said switch having an open state in which said first current flow path is interrupted; and

a second capacitive element electrically connected to said amplifier through a bridged network, said bridged network having a first closed state in which a second current flow path is provided between a first terminal of said second capacitive element and

said first terminal of said amplifier, said bridged network having a second closed state in which a third current flow path is provided between a second terminal of said second capacitive element and said first terminal of said amplifier, and said bridged network having an open state in which said second current flow path and said third current flow path are interrupted.

12. The circuitry of claim 11 wherein said first current flow path, said second current flow path, and said third current flow path include said current-carrying gradient coil.

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L32: Entry 12 of 13 File: USPT May 28, 1996

DOCUMENT-IDENTIFIER: US 5521507 A
TITLE: Gradient coil power supply and imaging method

Abstract Text (1):
In a magnetic resonance imaging system in which the read and phase directions are rotated with respect to the orthogonal gradient coil directions, a gradient coil is driven to generate a gradient waveform having a segment, either sinusoidal or linear, that approximates the sum of the simultaneous non-zero components of the read and phase gradient waveforms in the direction of the gradient coil. Resonant circuits, each including a gradient coil, generate simultaneous periodic gradient coil waveforms in which the integral over each waveform period is non-zero. First and second capacitive elements in the resonant power supply are electrically connected to the gradient coil through a switch and a bridged network, respectively. The bridged network selectively provides current flow paths between the coil and either of the terminals of the second capacitive element.

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Brief Summary Text (2):
This invention relates to producing modulated gradient fields in magnetic resonance imaging (MRI) systems.

Brief Summary Text (3):
In a typical MRI system, three electromagnetic gradient coils are driven using respective power supplies to generate magnetic field gradients in each of three orthogonal (e.g., x, y, and z) directions, termed "gradient coil directions." The magnetic fields generated by the gradient coils generally have components parallel to the direction of a main magnetic field, where the strengths of the components vary spatially (e.g., linearly) in each of the respective gradient coil directions. The gradient coils are typically driven to generate "read," "phase," and, "slice" gradient waveforms, where the plane or cross-section to be imaged lies parallel to the plane defined by the directions of the read and phase gradients.

Brief Summary Text (4):
A variety of gradient coil power supplies are known for generating magnetic field gradients for MRI systems. In some systems, the power supply consists only of an amplifier, which drives the gradient coil directly to produce the desired gradient waveforms. The amplifiers can be controlled to obtain images of planes that lie at oblique angles to the gradient coil directions.

Brief Summary Text (5):
In other MRI systems, such as those disclosed in Rzedzian U.S. Pat. No. 4,628,264, incorporated herein by reference in its entirety, the gradient coil is connected in parallel with a capacitor to form a parallel resonant circuit. And in still other MRI power supplies, such as those disclosed in Rzedzian et al. U.S. Pat. No. 5,285,161, incorporated herein by reference in its entirety, the gradient coil is connected in series with a capacitor to form a series resonant circuit. In both the parallel and the series resonant power supplies, an amplifier drives the coil-capacitor circuit at or near its resonant frequency, generating a sinusoidally varying gradient waveform. The power supplies can be controlled to interrupt the resonant sinusoidal waveform for periods of arbitrary duration.

Brief Summary Text (7):
In one general aspect of the invention, the read and phase directions are rotated with respect to the gradient coil directions. One of the gradient coils is driven to generate a gradient waveform having a segment, either sinusoidal or linear, that approximates the sum of the simultaneous non-zero components of the read and phase gradient waveforms in the direction of the gradient coil.

Brief Summary Text (8):
Among other advantages, this aspect of the invention allows the read-phase plane, that is, the clinical imaging (or scan) plane, to be rotated through one or more angles with respect to the gradient coil directions. Thus, an object in which the cross-section of interest does not lie perpendicular to any of the x, y, or z gradient coil axes need not by physically rotated in order to obtain a satisfactory image. Rather, the image plane itself can be rotated as necessary to obtain an image of the desired slice of the object.

Brief Summary Text (9):
Moreover, because the non-zero components of the read and phase gradient waveforms are generated simultaneously, for given gradient waveform frequencies and amplitudes the total time needed to sample a single image is shorter than if the non-zero components were generated sequentially.

Brief Summary Text (10):
In preferred embodiments, all three of the gradient coils are driven using resonant power supplies to generate periodic waveforms that approximate the summed components of the read and phase gradient waveforms in each of the x, y, and z gradient coil directions. In particular, the integral over one period of each gradient coil waveform equals the integral over the same period of the summed components of the read and phase gradient waveforms in the direction of that waveform. Each power supply includes two capacitive elements that are precharged prior to the initiation of the gradient waveforms to generate sinusoidal resonances at desired amplitudes when switches connecting the respective capacitive elements to the coils are closed. In operation, one of the two switches is opened (e.g., after a half-period sinusoidal segment has been generated) at substantially the same time that the other switch is closed.

Brief Summary Text (11):
In another aspect of the invention, a plurality of resonant circuits, each including a gradient coil, are driven to generate simultaneous periodic gradient waveforms in which the integral over each waveform period is non-zero.

Brief Summary Text (12):
Among other advantages of this aspect of the invention, the resonant circuits can be driven at their respective resonant frequencies, reducing the amount of power necessary to produce a gradient waveform of a desired amplitude (e.g., a DC-offset sinusoidal waveform or a waveform comprised of sinusoidal segments).

Brief Summary Text (13):
Another aspect of the invention includes a resonant power supply in which first and second capacitive elements are electrically connected to the gradient coil through a switch and a bridged network, respectively. The bridged network selectively provides current flow paths between the coil and either of the terminals of the second capacitive element.

Brief Summary Text (14):
In preferred embodiments, a controller controls the switch and the bridge in accordance with a predetermined, periodic pattern. The bridge includes four bipolar switches, two connected to one terminal of the second capacitive element, and two connected to the other. An amplifier connected to the coil drives the coil with a voltage signal synchronized to the gradient waveform.

Drawing Description Text (2):
FIG. 1 is a cross-sectional, diagrammatic view of an arrangement of MRI coils around a subject body.

Drawing Description Text (5):
FIG. 3 is a timing diagram showing signals used in an echo planar imaging (EPI) MRI sequence.

Drawing Description Text (7):
FIG. 4b is a detail view of one portion of one of the signals of FIG. 4a.

Drawing Description Text (9):
FIG. 5b is a detail view of one portion of one of the signals of FIG. 5a, and showing a switch control sequence for the structure depicted in FIG. 2a.

Drawing Description Text (10):
FIG. 5c is a detail view showing the difference between the current signal shown in FIG. 5b and the current signal shown in FIG. 4b.

Drawing Description Text (12):
FIG. 6b is a detail view of one portion of one of the signals of FIG. 6a, and showing a switch control sequence for the structure depicted in FIG. 2a.

Drawing Description Text (13):
FIG. 7 is a timing diagram showing signals used in another EPI MRI sequence.

Drawing Description Text (15):
FIG. 8b is a detail view of one portion of one of the signals of FIG. 8a, and showing a switch control sequence for the structure depicted in FIG. 2a.

Drawing Description Text (19):
FIG. 10b is a detail view of one portion of one of the signals of FIG. 10a.

Detailed Description Text (2):
With reference to FIG. 1, magnetic coils 10 are oriented in relation to orthogonal x, y, and z axes. As described in U.S. Pat. No. 4,628,264 to Rzedzian, incorporated herein in its entirety by reference, a whole-body coil 12 generates a static main magnetic field, and gradient coils 14, 15, 16 (shown diagrammatically) provide magnetic field gradients G.sub.x, G.sub.y, and G.sub.z in the respective x, y, and z gradient coil directions. Coils 10 surround subject body 18. A separate resonant power supply (RPS) 20, 21, 23 drives each of gradient coils 14, 15, 16.

Detailed Description Text (3):
A topology for RPS 20 for driving gradient coil 14 is shown in FIG. 2a. RPS 20 includes a controllable gradient amplifier 22, such as a linear amplifier or a switching amplifier, in series with gradient coil 14 and two bridged capacitor networks 24a, 24b. Each bridged capacitor network 24a, 24b includes four switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d, a capacitor 30a, 30b, and an associated charging circuit 32a, 32b. Switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d may be bipolar switches, such as insulated gate bipolar transistors (IGBTs), or unipolar switches such as silicon controlled rectifiers arranged in pairs. A suitable charging circuit 32a, 32b is described in U.S. Pat. No. 5,245,287 to Rzedzian, incorporated herein in its entirety by reference. Alternatively, a single charging circuit that can be switched between capacitors 30a, 30b can be substituted for charging circuits 32a, 32b, or capacitors 30a, 30b can be charged directly from amplifier 22. A run/charge controller 33 asserts control signals for controlling the state of switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d, and also controls the operation of chargers 32a, 32b and amplifier 22. In order to accommodate transients in the voltage signal supplied by amplifier 22 when switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d are opened and closed by controller 33, it may be necessary to include additional switches and snubbers (not shown) in RPS 20.

Detailed Description Text (4):
RPSs 21, 23, for driving gradient coils 15, 16, are identical to RPS 20, and are similarly controlled.

Detailed Description Text (5):
An alternate RPS 35 is shown in FIG. 2b. (For convenience and clarity, many of the numerals used in FIG. 2a are used to identify also the principle components and subassemblies in FIG. 2b, as well as in the other alternate RPS embodiments shown and described herein.) RPS 35 is identical to RPS 20, except switches 26b, 26c have been eliminated, and switch 26d has been replaced with a permanently conducting section.

Detailed Description Text (6):
As disclosed in Rzedzian U.S. Pat. No. 4,940,941, incorporated herein by reference in its entirety, and also with reference to FIG. 3, echo planar imaging (EPI), known in the prior art, involves the generation of gradient waveforms in orthogonal read, phase, and slice directions. A gradient waveform is a representation of how the strength of a

magnetic field gradient (e.g., in units of gauss/cm) varies with time. For each gradient coil 14, 15, 16, there is a direct relationship between the strength of the magnetic field gradient and the magnitude of the current signal supplied to the gradient coil. Thus, if the read, phase, and slice directions are parallel to the x, y, and z gradient coil directions, the respective current signals used to drive gradient coils 14, 15, 16 will generally have the same shapes as the gradient waveforms shown in FIG. 3, although the relative amplitudes of the current signals need not be (and in general will not be) identical to the relative amplitudes of the gradient waveforms.

Detailed Description Text (7):
In EPI, as well as in some other imaging techniques, a slice-select gradient 34 (e.g., a square or trapezoidal pulse of amplitude I.sub.s) is first generated in the slice direction, followed by pre-phasing gradient pulses 36, 38 in the read and phase directions and, optionally, a refocus gradient pulse 40 in the slice direction.

Detailed Description Text (8):
The acquisition sequence, which follows the above pulse sequence, includes a read-out gradient waveform 42 in the read direction and a phase-coding gradient waveform 44 in the phase direction. Read-out gradient waveform 42 is a sinusoid of amplitude I.sub.r :

Detailed Description Text (9):
Phase-coding gradient waveform 44 is a series of positive, relatively high-frequency cosine "blips" of amplitude I.sub.p centered around the zero-crossings 46 (both positive-going and negative-going) of read-out gradient waveform 42:

Detailed Description Text (10):
where T.sub.r equals .pi./.omega..sub.r, one-half of the period of the read-out gradient waveform, and T.sub.p equals .pi./.omega..sub.p, one-half of the period of the phase-coding gradient waveform. Alternatively, the blips of phase-coding gradient waveform 44 could be negative.

Detailed Description Text (11):
Slice-select gradient pulse 38, together with a simultaneously generated radio-frequency (RF) excitation pulse, excite the nuclei (not shown) in a planar slice of subject body 18. The axial location of this planar slice, which lies perpendicular to the slice direction, is determined by the frequency of the RF excitation pulse. To generate an image, read-out gradient waveform 34 and phase-coding gradient waveform 36 are then employed to evaluate the spatially varying density of the excited nuclei in the selected slice. Thus, slice-select gradient pulse 38 determines the cross-section of subject body 18 (i.e., the image plane) that is imaged. Accordingly, if gradient coils 14, 15, 16 are driven to generate the gradient waveforms depicted in FIG. 3, the image plane will be perpendicular whichever of the x-, y-, or z-axis gradient coils 14, 15, 16 is used to generate slice-select gradient 38.

Detailed Description Text (12):
In many situations, it is desirable to image an object, e.g., an organ such as a human heart, in which the cross-section of interest is not perpendicular to, and cannot conveniently be physically rotated to an orientation perpendicular to, the x, y, or z axes of coils 10. In such instances it is advantageous to rotate instead the image plane, as determined by the orthogonal read, phase, and slice directions, to the desired orientation. To accomplish this using EPI techniques, the read, phase, and slice gradient waveforms shown in FIG. 3 are generated in orthogonal read, phase, and slice directions that are rotated through at least one non-zero angle with respect to the x, y, and z gradient coil directions. Because of this rotation, each of the desired read, phase, and slice waveforms has components in at least one of the x, y, and z gradient coil directions. Thus, as described in greater detail below, the image plane can be rotated by driving gradient coils 14, 15, 16 to generate gradient waveforms that equal or approximate the sums of those components of the read, phase, and slice gradient waveforms that lie in the respective x, y, and z gradient coil directions.

Detailed Description Text (13):
The rotation of any orthogonal cartesian set of axes with respect to a given frame of reference can be described by three angles, .theta., .phi., and .psi.. Known as Euler angles, .theta. and .phi. are the polar and azimuthal angles, respectively, and .psi. represents the rotational orientation of the image in the image plane. Thus, .theta. and .phi. determine the orientation of the slice plane with respect to the x, y, and z axes, and .psi. determines the orientation of the displayed MRI image of that slice plane.

Detailed Description Text (14):
For a given set of Euler angles, the rotation from the desired read, phase, and slice directions to the x, y, and z axes of coils 10 is described by the following relation: ##EQU1##

Detailed Description Text (15):
Thus, during the slice-select phase, when I.sub.r and I.sub.p both equal zero, slice-select gradient pulse 38 of amplitude I.sub.s is generated in the desired rotated slice direction when:

Detailed Description Text (16):
Pre-phasing gradient pulses 36, 38 and refocus pulse 40 are generated in the rotated directions in a similar manner.

Detailed Description Text (17):
During the acquisition sequence, when I.sub.s equals zero, the desired read-out and phase-coding gradients are generated in the desired rotated read and phase directions when:

Detailed Description Text (19):
Thus, in order to generate the read, phase, and slice gradient waveforms shown in FIG. 3 in a desired rotated frame of reference, the desired angles of rotation .theta., .phi., and .psi. are substituted into equations (4), (8), and (9). For instance, in order to generate the EPI read, phase, and slice gradient waveforms in a frame of reference that is rotated through 30.degree. and 75.degree. with respect to the x, y, and z axes, the x, y, and z gradient coils 14, 15, 16 can be driven with the current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) shown in FIG. 4a. Current signal I.sub.x (t), together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 4b.

Detailed Description Text (20):
The pure sinusoidal portion of the desired waveform (i.e., the portion described by equation (8)) is generated, as described in greater detail below, using bridged capacitor network 24a. Capacitor 30a and coil 14 provide a circuit having a resonant frequency of .omega..sub.r when: ##EQU2## where L is the inductance of gradient coil 14 and C.sub.1 is the capacitance of capacitor 30a. Because L and .omega..sub.r are generally given, capacitor 30a should thus be selected such that:

Detailed Description Text (21):
The capacitors for the first bridged capacitor networks of the resonant power supplies of the other two gradient coils 15, 16 are likewise chosen to provide a circuit having a resonant frequency of .omega..sub.r.

Detailed Description Text (22):
To avoid transients, prior to initiating a gradient waveform readout sequence, capacitor 30a is precharged to an initial voltage V.sub.1i equal to the peak capacitor voltage generated when gradient coil 14 resonates with the desired coil current I.sub.r a.sub.ri, as provided by equation (8). As described in U.S. Pat. No. 5,285,161 issued to Rzedzian et al.: ##EQU3##

Detailed Description Text (23):
The summed portion of the desired waveform (i.e., the portion described by equation (9)) can be approximated by a half-period phase-offset cosine segment having the same frequency .omega..sub.p as the phase blips of phase gradient 36. For the negative-going portion of the gradient waveform, this segment is described by:

Detailed Description Text (24):
For the positive-going portion of the gradient waveform, the segment is described by:

Detailed Description Text (25):
The phase-offset cosine segment of the desired generalized waveform is generated, as described in greater detail below, by employing bridged capacitor network 24b. The capacitance C.sub.2 of capacitor 30b is chosen to provide the desired frequency .omega..sub.p :

Detailed Description Text (26):
The capacitors for the second bridged capacitor networks of the resonant power supplies of the other two gradient coils 15, 16 are likewise chosen to provide a circuit having

a resonant frequency of .omega..sub.p.

Detailed Description Text (27):
The amplitude I.sub.2i of the phase-offset cosine segment should be such that the integral over this segment equals the integral over one segment of the summed portion of the desired waveform. Accordingly: ##EQU4## Note that the integrals of the phase-offset cosine segments described by equations (13) and (14) are both positive.

Detailed Description Text (28):
The values of I.sub.r and I.sub.p are derived from imaging requirements: ##EQU5## Where .gamma. is the gyromagnetic ratio, ff is the strength of the gradient coil, .DELTA. is the image resolution, and FOV is the field of view (here, in the phase direction).

Detailed Description Text (29):
The current waveform of coil 14 should be continuous everywhere, including at the point of transition between the pure sinusoidal portion and the phase-offset cosine segment. At this point t.sub.i, which occurs T.sub.p /2 before each zero-crossing 40, equation (8) thus equals equation (13): ##EQU6## Noting that t.sub.i modT.sub.r equals -T.sub.p /2, one-quarter of the period of phase blip 36, this expression can be rearranged to find .eta..sub.i : ##EQU7##

Detailed Description Text (30):
Using .eta..sub.i, the amplitude I.sub.2i of the half-period, phase-offset cosine segment can be determined from equation (16). These values, together with the relationship ##EQU8## can then be used to calculate the initial precharge voltage V.sub.2i on capacitor 30b that provides the desired phase offset .eta..sub.i : ##EQU9##

Detailed Description Text (31):
The current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) used to drive the x, y, and z gradient coils 14, 15, 16 in order to generate the EPI read, phase, and slice gradient waveforms shown in FIG. 3 in a frame of reference that is rotated through (for example) 30.degree. and 75.degree. with respect to the x, y, and z axes are shown in FIG. 5a. In short, based on imaging requirements, controller 33 determines the desired read, phase, and slice waveforms in the respective read, phase, and slice directions. From these desired waveforms, controller 33 performs the appropriate transforms to determine the precharge voltages on capacitors 30a, 30b, as well as the current waveform to be provided by amplifier 22. As shown in FIG. 5b and described below, controller 33 controls switches 26a, 26b, 26c, 26d; 28a, 28b, 28c, 28d to cause RPS 20 to generate gradient field waveforms that approximate the summed x, y, and z components of the desired read, phase, and slice waveforms.

Detailed Description Text (32):
The slice-select, pre-encode, and refocus pulses 34, 36, 38 are generated by driving gradient coils 14, 15, 16 directly with their respective gradient amplifiers to generate current pulses of the appropriate amplitude. Thus, for example, during the slice-select period, only switches 26a, 26b in RPS 20 are closed, and gradient amplifier 22 is controlled to supply the requisite current pulse of amplitude I.sub.s a.sub.sx, as provided by equation (5).

Detailed Description Text (33):
Current signal I.sub.x (t) from FIG. 5a, together with its corresponding voltage signal V.sub.x (t) and the switch control sequence for RPS 20, are shown in detail in FIG. 5b.

Detailed Description Text (34):
Prior to initiating the acquisition sequence, capacitors 30a, 30b are precharged to precharge voltages V.sub.1i, V.sub.2i. Once capacitors 30a, 30b have been charged, run/charge controller 33 initiates the acquisition sequence at t.sub.0 by asserting control signals to close switches 26a, 26d (for the embodiment shown in FIG. 2b, controller 33 closes switch 26a). Capacitor 30a then begins to discharge into gradient coil 14, causing gradient coil 14 to generate a gradient waveform segment having frequency .omega..sub.r.

Detailed Description Text (35):
Gradient amplifier 22, which is synchronized to the phase and frequency of the gradient waveform by controller 33, e.g., by monitoring the current of coil 14 and comparing the sensed current to the stored representative waveform determined by controller 33, provides energy to the resonant system in the form of voltage to compensate for

resistive and other parasitic losses in RPS 20.

Detailed Description Text (36):
At time t.sub.1, which occurs T.sub.p /2 before the first zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 26a, 26d, and substantially simultaneously closes switches 28a, 28d. Capacitor 30b then begins to discharge into gradient coil 14, causing gradient coil 14 to generate a gradient waveform having frequency .omega..sub.p. Because of precharge voltage V.sub.2i, the ensuing segment of the gradient waveform is a cosine of amplitude I.sub.2i having a phase-offset .eta..sub.i. Because this is the negative-going portion of the gradient waveform, this phase-shifted cosine is described mathematically by equation (13).

Detailed Description Text (37):
At time t.sub.2, which occurs T.sub.p /2 after the first zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 28a, 28d, and substantially simultaneously closes switches 26a, 26d. Capacitor 30a, the voltage on which has remained essentially constant since t.sub.1, then begins to discharge into gradient coil 14, causing gradient coil 14 to generate another gradient waveform segment having frequency of .omega..sub.r.

Detailed Description Text (38):
At time t.sub.3, which occurs T.sub.p /2 before the next zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 26a, 26d and substantially simultaneously closes switches 28b, 28c. The polarity of capacitor 30b, the voltage on which has remained essentially constant since t.sub.2, is thus reversed in RPS 20 relative to its polarity from t.sub.1 to t.sub.2. Gradient coil 14 again generates a gradient waveform segment having frequency .omega..sub.p. Because this is the positive-going portion of the gradient waveform, the ensuing phase-shifted cosine is described mathematically by equation (14).

Detailed Description Text (39):
At time t.sub.4, which occurs T.sub.p /2 after the next zero crossing 46 of the read-out gradient waveform, controller 33 opens switches 28b, 28c, and substantially simultaneously closes switches 26a, 26d. Capacitor 30a, the voltage on which has remained essentially constant since t.sub.3, then begins to discharge into gradient coil 14, causing gradient coil 14 to generate another gradient waveform segment having a frequency of .omega..sub.r.

Detailed Description Text (40):
This continues until time t.sub.5, which occurs T.sub.p /2 before the next zero crossing 46 of the read-out gradient waveform. At t.sub.5, the cycle described above starting at time t.sub.1 repeats. Thus, the portion between t.sub.1 and t.sub.5 represents one period of the gradient waveform. The duration of this period is 2T.sub.r. Because the integrals of the phase-shifted cosine segments of each period of the waveform are both positive, the integral over one period of the waveform is positive.

Detailed Description Text (41):
As noted, RPS 20 is controlled to approximate the summed portion of the desired waveform (i.e., the portion described by equation (9)) with a half-period phase-offset cosine segment having the same frequency .omega..sub.p as the phase blips of phase gradient 36. The effect of this approximation is demonstrated in FIG. 5c, which shows the difference between the "approximate" x-coil current signal I.sub.x (t) of FIG. 5b and the "ideal" x-coil current signal I.sub.x (t) of FIG. 4b.

Detailed Description Text (42):
Other current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) for approximating the read, phase, and slice gradient waveforms shown in FIG. 3 in a frame of reference that is rotated through, for example, 30.degree. and 75.degree. with respect to the x, y, and z axes are shown in FIG. 6a. Current signal I.sub.x (t), together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 6b.

Detailed Description Text (43):
Referring to FIG. 6b, a single period of a waveform 68 starting at t.sub.1 includes a positive constant-current (and thus also constant-gradient) segment 70 of duration T.sub.h (i.e., t.sub.2 minus t.sub.1), followed at t.sub.2 by a sinusoidal segment 72 of frequency .omega..sub.r, followed at t.sub.3 by a positive horizontal, constant-current segment 74 (i.e., a sinusoidal segment with a frequency equal to zero) of duration T.sub.h, followed at t.sub.4 by a sinusoidal segment 76 of frequency

.omega..sub.r. At t.sub.5, when segment 76 concludes, the waveform repeats. The amplitude of segments 72, 76 is I.sub.r a.sub.ri, and the amplitude I.sub.2i of segments 62, 66 is chosen such that the integral of waveform 68 over each of these segments equals the integral over one segment of the summed portion of the desired waveform, as provided by equation (9): ##EQU10##

Detailed Description Text (45):
RPS 20 is controlled to generate current signal I.sub.x (t), and RPSs 21 and 23 are controlled in a similar manner to generate current signals I.sub.y (t) and I.sub.z (t), respectively. The control sequence to generate waveform 68 is shown in FIG. 6b. Once capacitor 30a has been charged, run/charge controller 33 initiates the acquisition sequence at t.sub.0 by asserting control signals to close switches 26a, 26d. Capacitor 30a then begins to discharge into gradient coil 14, causing gradient coil 14 to generate a segment 78 of gradient waveform 68 having a frequency of .omega..sub.r. On the negative-going portion of segment 78, when (at time t.sub.1) the current of coil 14 equals I.sub.2i, as provided by equation (24), controller 33 opens switches 26a, 26d, and substantially simultaneously closes switches 28a, 28b. Gradient amplifier 22 is then controlled to supply I.sub.2i for a duration of T.sub.p (until time t.sub.2).

Detailed Description Text (46):
At time t.sub.2, controller 33 opens switches 28a, 28b, and substantially simultaneously closes switches 26a, 26d, allowing capacitor 30a, the voltage on which has remained essentially constant since t.sub.1, to resume discharging into gradient coil 14, causing gradient coil 14 to generate segment 72 of gradient waveform 68. On the positive-going portion of segment 72, when (at time t.sub.3) the current of coil 14 equals I.sub.2i, controller 33 opens switches 26a, 26d, and substantially simultaneously closes switches 28a, 28b. Gradient amplifier 22 is again controlled to supply I.sub.2i for a duration of T.sub.p (until time t.sub.4). Segment 76, which concludes at time t.sub.5, is provided in a manner similar to segment 78.

Detailed Description Text (47):
The portion between t.sub.1 and t.sub.5 represents one period of gradient waveform 68. Because the integrals of positive horizontal segments 70, 74 of waveform 68 are positive, the integral over one period of waveform 68 is positive.

Detailed Description Text (48):
The waveform segments between t.sub.1 and t.sub.2 and t.sub.3 and t.sub.4 need not be horizontal segments 70, 74. Rather, amplifier 22 may be controlled during these time periods to generate a variety of different waveform segment shapes (e.g., lines of constant, nonzero slope). At least three factors should be considered when selecting these waveform segments. First, the amplitude and the frequency or frequencies of the waveform should be within the bandwidth of amplifier 22. Because amplifier 22 drives coil 14 directly during these segments, the frequency of the waveform need not be determined with reference to the resonant frequencies of RPS 20. Second, to provide a continuous current waveform, the waveform segments should be continuous with adjacent sinusoidal waveform segments 72, 76, 78. Third, the waveform segments should be chosen so that the integral over each segment equals the integral over the same time period of the summed portion of the desired waveform, as provided by equation (9).

Detailed Description Text (49):
An alternate EPI sequence is shown in FIG. 7. This sequence is similar to that shown in FIG. 3 (having a read-out gradient waveform 55, a phase-coding gradient waveform 57, and a slice-select gradient waveform 59 of amplitudes I.sub.r, I.sub.p, and I.sub.s, respectively), except read-out gradient waveform 55 is equal to zero when phase-coding gradient waveform 57 is nonzero. Accordingly, with the exception of prephasing gradient pulses 61, 63, when any one gradient waveform is nonzero, the other two gradient waveforms are zero.

Detailed Description Text (50):
In order to generate the EPI read, phase, and slice gradient waveforms shown in FIG. 7 in a frame of reference that is rotated, for example, through 30.degree. and 75.degree. with respect to the x, y, and z axes, the x, y, and z gradient coils 14, 15, 16 can be driven with the current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) shown in FIG. 8a. Current signal I.sub.x (t), together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 8b.

Detailed Description Text (51):
Referring to FIG. 8b, a single period 58 of current signal I.sub.x (t) starting at t.sub.O includes a positive, half-period sinusoidal segment 60 of frequency

.omega..sub.r, followed at t.sub.1 by a positive, half-period sinusoidal segment 62 of frequency .omega..sub.p, followed at t.sub.2 by a negative, half-period sinusoidal segment 64 of frequency .omega..sub.r, followed at t.sub.3 by a positive, half-period sinusoidal segment 66 of frequency .omega..sub.p. At t.sub.4, when segment 66 concludes, the waveform repeats. The amplitude of segments 60, 64 is I.sub.r a.sub.ri, as provided by equation (8), and the amplitude of segments 62, 66 is I.sub.p a.sub.pi, as provided by equation (16), where .eta..sub.i equals zero. Thus, segments 60, 64 are scaled to provide (together with the waveforms on the other two axes) read-out gradient 55 of amplitude I.sub.r in the desired rotated orientation. Similarly, segments 62, 66 are scaled to provide (together with the waveforms on the other two axes) phase-coding gradient 57 of amplitude I.sub.s in the desired rotated orientation. The precharge voltage V.sub.1i on capacitor 30a is given by equation (12). Similarly, the precharge voltage V.sub.2i on capacitor 30b is: ##EQU11##

Detailed Description Text (52):
RPS 20 is controlled to generate current signal I.sub.x (t), and RPSs 21 and 23 are controlled in a similar manner to generate current signals I.sub.y (t) and I.sub.z (t), respectively. The control sequence used to generate waveform 58 is identical to that used to generate the waveform in FIG. 5b. The portion between t.sub.0 and t.sub.4 represents one period of gradient waveform 58. Note that for the same values of .omega..sub.r and .omega..sub.p, a single period of the waveform is longer, by 2T.sub.p, than the waveform. Because the integrals of segments 62, 66 of waveform 58 are positive, the integral over one period of waveform 58 is positive.

Detailed Description Text (53):
Another topology for an RPS 100 for driving gradient coils 14 to provide waveform components of desired waveforms in rotated read, phase, and slice directions is shown in FIG. 9a. Amplifier 22, gradient coil 14, switch 104, and capacitor 30a are all connected in series (the controlling circuitry and the associated control lines are not shown in FIG. 9a). Current source 102, which supplies a constant current I.sub.B, is connected in parallel with capacitor 30a. A charging circuit and a controller (not shown) are provided as described in connection with FIGS. 2a and 2b.

Detailed Description Text (54):
Current signals I.sub.x (t), I.sub.y (t), and I.sub.z (t) for approximating the read, phase, and slice gradient waveforms shown in FIG. 3 in a frame of reference that is rotated through, for example, 30.degree. and 75.degree. with respect to the x, y, and z axes are shown in FIG. 10a. Current signal I.sub.x (t) 120 generated by RPS 100, together with its corresponding voltage signal V.sub.x (t), are shown in detail in FIG. 10b. Current signals I.sub.y (t) and I.sub.z (t) are generated by respective power supplies (not shown) that are substantially identical to RPS 100.

Detailed Description Text (55):
Although difficult to see in FIG. 10b, waveform 120, which has a frequency of .omega..sub.r, is positively DC-offset by an amount I.sub.B (and accordingly, the magnitude of voltage signal V.sub.x (t) increases throughout the EPI sequence). The value of I.sub.B is chosen such that the integral over one period of waveform 120 equals the integral, over one period of read-out gradient waveform 42, of phase-coding gradient waveform 44. Thus: ##EQU12##

Detailed Description Text (56):
The precharge voltage V.sub.1i on capacitor 30a is as given above by equation (12). Once capacitor 30a has been charged, the run/charge controller initiates the acquisition sequence at t.sub.0 by asserting control signals to close switch 104. Note that the integral over one period of waveform 120 is positive.

Detailed Description Text (57):
An alternate topology for generating waveforms of the type depicted in FIGS. 10a and 10b is shown in FIG. 9b. RPS 106 is similar to RPS 20 shown in FIG. 2a, except a current source 108 for supplying a constant current I.sub.B has been substituted for bridged capacitor network 24b.

Detailed Description Text (58):
Another topology for an RPS 150 for driving gradient coils 14 to provide waveform components of the desired waveforms in rotated read, phase, and slice directions is shown in FIG. 11 (the controlling circuitry and the associated control lines are not shown in FIG. 11). RPS 150 is similar in construction to RPS 20 shown in FIG. 2a, except bridged capacitor networks 24a, 24b are connected in series in RPS 150, and switch 152 is connected in parallel with switches 28a, 28b. The operation of RPS 150 is

also similar to that of RPS 20. The precharge voltage V.sub.1i on capacitor 30a provided by charger 32a is as given above by equation (12). The pure sinusoidal portion of the desired waveform (i.e., the portion described by equation (8)) is then generated by closing only switches 26a, 26b, 152, and synchronizing amplifier 22 to the current passing through coil 14.

Detailed Description Text (59):
An approximation of the summed portion of the desired waveform (i.e., the portion described by equation (8)) is then generated by opening switch 152 and closing switches 28a, 28d. This connects capacitors 30a, 30b in series with coil 14 and amplifier 22. The effective capacitance C.sub.e of this resonant circuit is: ##EQU13## The capacitance C.sub.1 of capacitor 30a is selected in accordance with equation (11). The desired effective capacitance C.sub.e (and thus also the capacitance C.sub.2 of capacitor 30b) is then found by:

Detailed Description Text (60):
The desired phase offset is provided when capacitor 30b is precharged, by charger 32b, to a precharge voltage V.sub.2i : ##EQU14##

Detailed Description Text (61):
Because capacitor 30a remains in the current flow path to generate the approximation segment, at the conclusion of the segment the charge on the capacitor is not equal to the charge immediately preceding the beginning of the segment. This charge difference can be accommodated through appropriate control of the linear amplifier, charging circuit 32a, or a dedicated charge-correction circuit (comprising, e.g., an additional charged capacitor, not shown, that can be electrically connected in parallel with capacitor 30a at the conclusion of the approximation segment).

Detailed Description Text (62):
Although in the above-described embodiments the three x, y, and z gradient coils 14, 15, 16 are all driven using RPSs 20, 100, 150 or the like, acceptable performance may be realized where only two of the three gradient coils are driven using RPSs 20, 100, 150.

Detailed Description Text (63):
In one example of such an embodiment, the x- and y-axis gradient coils are driven using RPSs 20, 100, 150 or the like, and the z-axis gradient coil is driven directly by a gradient amplifier (not shown). Note from equation (4) that if .psi. is restricted to zero degrees, which constrains the rotation of the displayed MRI image, a.sub.rz also equals zero. Thus, the z-axis gradient coil provides no component of read-out gradient 42 when .psi.=0. During the acquisition period, the z-axis gradient coil provides only a component (I.sub.p a.sub.pz) of phase-coding gradient 44. Because phase-coding gradient 44 generally has a much smaller amplitude (I.sub.p) than read-out gradient 42, this component can be generated by driving the z-axis gradient coil directly with its associated gradient amplifier.

Detailed Description Text (64):
If instead the y- and z-axis gradient coils are driven using RPSs 20, 100, 150 or the like, and the x-axis gradient coil is driven directly by a gradient amplifier (not shown), the x-axis gradient coil provides no component of read-out gradient 42 when: ##EQU15##

Detailed Description Text (65):
And if the y-axis gradient coil is the one that is driven directly by a gradient amplifier (not shown), that gradient coil provides no component of read-out gradient 42 when: ##EQU16##

Detailed Description Text (68):
For instance, the phase blip need not be centered around the zero-crossing of the read out gradient waveform, and need not be a cosine (i.e., a phase-shifted sinusoid). And, as disclosed in Rzedzian U.S. Pat. Nos. 4,628,264 and 5,285,161, the read out gradient waveform can be other than a regular sinusoid, e.g., the read out waveform may be comprised of a series of sinusoidal segments interconnected by horizontal segments. Furthermore, the approximated portion of the summed waveform can be any linear segment (e.g., a straight line at any angle), instead of just a horizontal segment. Thus, the approximation of the summed components of the read and phase gradient waveforms can be either a sinusoidal or a linear segment.

Detailed Description Text (69):

Moreover, although in each of the above-described embodiments the capacitors are connected in series with the gradient coil, they could instead be connected in parallel. And instead of using multiple capacitors to generate different segments of the gradient waveform, the gradient coil could be connected to a capacitor and another inductive coil. The second coil could be switched into and out of the circuit as necessary to generate the desired segments.

CLAIMS:

1. A method of generating magnetic field waveforms to approximate a desired set of read and phase gradient waveforms in respective orthogonal read and phase directions for echo planar magnetic resonance imaging, said method comprising the steps of:

providing a first gradient coil for generating a magnetic field gradient in a first one of three orthogonal gradient coil directions;

said gradient coil directions rotated with respect to said read and phase directions so that said desired read and phase gradient waveforms have simultaneous non-zero components in said first one of said gradient coil directions;

driving said first gradient coil to generate a first gradient waveform having a first segment that approximates the sum of said simultaneous non-zero components of said read and phase gradient waveforms in said first one of said gradient coil directions, said first segment being either a sinusoidal segment or a linear segment.

2. Apparatus for generating magnetic field waveforms to approximate a desired set of read and phase gradient waveforms in respective orthogonal read and phase directions for echo planar magnetic resonance imaging, said apparatus comprising:

a first gradient coil for generating a magnetic field gradient in a first one of three orthogonal gradient coil directions;

said gradient coil directions rotated with respect to said read and phase directions so that said desired read and phase gradient waveforms have simultaneous non-zero components in said first one of said gradient coil directions;

means for driving said first gradient coil to generate a first gradient waveform having a first segment that approximates the sum of said simultaneous non-zero components of said read and phase gradient waveforms in said first one of said gradient coil directions, said first segment being either a sinusoidal segment or a linear segment.

3. The subject matter of claims 1 or 2 further comprising:

a second gradient coil for generating a magnetic field gradient in a second one of said three orthogonal gradient coil directions;

said gradient coil directions rotated with respect to said read and phase directions so that said desired read and phase gradient waveforms have simultaneous non-zero components in said second one of said gradient coil directions;

means for driving said second gradient coil to generate a second gradient waveform having a first segment that approximates the sum of said simultaneous non-zero components of said read and phase gradient waveforms in said second one of said gradient coil directions, said first segment being either a sinusoidal segment or a linear segment.

4. The subject matter of claim 3 further comprising:

a third gradient coil for generating a magnetic field gradient in a third one of said three orthogonal gradient coil directions;

said gradient coil directions rotated with respect to said read and phase directions so that said desired read and phase gradient waveforms have simultaneous non-zero components in said third one of said gradient coil directions;

means for driving said third gradient coil to generate a third gradient waveform having a first segment that approximates the sum of said simultaneous non-zero components of said read and phase gradient waveforms in said third one of said gradient coil directions, said first segment being either a sinusoidal segment or a linear segment.

5. The subject matter of claims 1 or 2 wherein said first gradient coil is driven to generate said first gradient waveform by a resonant power supply.

6. The subject matter of claim 5 wherein said resonant power supply includes a first capacitive element electrically connected to said first gradient coil through a first switch, said resonant circuit generating said first segment when said first switch is closed.

7. The subject matter of claim 6 wherein said first capacitive element is precharged prior to the initiation of said first gradient waveform to store energy in an amount sufficient to produce a sinusoidal resonance at a first desired amplitude when said first switch is closed.

8. The subject matter of claim 6 wherein said resonant power supply includes a second capacitive element electrically connected to said first gradient coil through a second switch, said resonant circuit generating a second segment of said first gradient waveform when said second switch is closed.

9. The subject matter of claim 8 wherein said second capacitive element is precharged prior to the initiation of said first gradient waveform to store energy in an amount sufficient to produce a sinusoidal resonance at a second desired amplitude when said second switch is closed.

10. The subject matter of claim 8 wherein said first switch is opened to terminate said first segment at substantially the same time said second switch is closed to initiate said second segment.

13. The subject matter of claims 1 or 2 wherein said first gradient waveform is periodic.

14. The subject matter of claim 13 wherein an integral over one period of said first gradient waveform approximately equals an integral over said period of the sum of said components of said read and phase gradient waveforms in said first one of said gradient coil directions.

15. A method of generating a magnetic field for magnetic resonance imaging, said method comprising the steps of:

providing a plurality of resonant circuits, each of said resonant circuits including a capacitive element electrically connected to a current-carrying gradient coil to provide a current flow path between said capacitive element and said coil for generating at least a portion of a periodic magnetic field gradient waveform; and

driving said plurality of resonant circuits to generate simultaneous periodic gradient waveforms, wherein an integral over one period of each of said waveforms is non-zero and wherein at least one of said periodic gradient waveforms is a DC-offset sinusoidal waveform.

16. Circuitry for generating a magnetic field in a magnetic resonance imaging system, said circuitry comprising:

a resonant power supply including:

a current-carrying gradient coil for generating a magnetic field gradient;

a first capacitive element electrically connected to said gradient coil through a switch, said switch having a closed state in which a first current flow path is provided between said first capacitive element and said coil, and said switch having an open state in which said first current flow path is interrupted; and

a second capacitive element electrically connected to said gradient coil through a bridged network, said bridged network having a first closed state in which a second current flow path is provided between a first terminal of said second capacitive element and said coil, said bridged network having a second closed state in which a third current flow path is provided between a second terminal of said second capacitive element and said coil, and said bridged network having an open state in which said second current flow path and said third current flow path are interrupted.

17. The circuitry of claim 16 wherein said resonant power supply includes a controller for selecting said states of said switch and said bridged network to generate a gradient waveform.

18. The circuitry of claim 17 wherein said controller selects said states of said switch and said states of said bridged network in accordance with a predetermined, periodic pattern.

19. The circuitry of claim 18 wherein said bridged network includes four switches.

20. The circuitry of claim 19 wherein said switches of said bridged network are bipolar.

21. The circuitry of claim 19 wherein two of said switches of said bridged network connect to said first terminal of said second capacitive element, and a different two of said switches of said bridged network connect to said second terminal of said second capacitive element.

22. The circuitry of claim 16 wherein said resonant power supply includes an amplifier connected to said coil to drive said coil with a voltage signal synchronized to said gradient waveform.